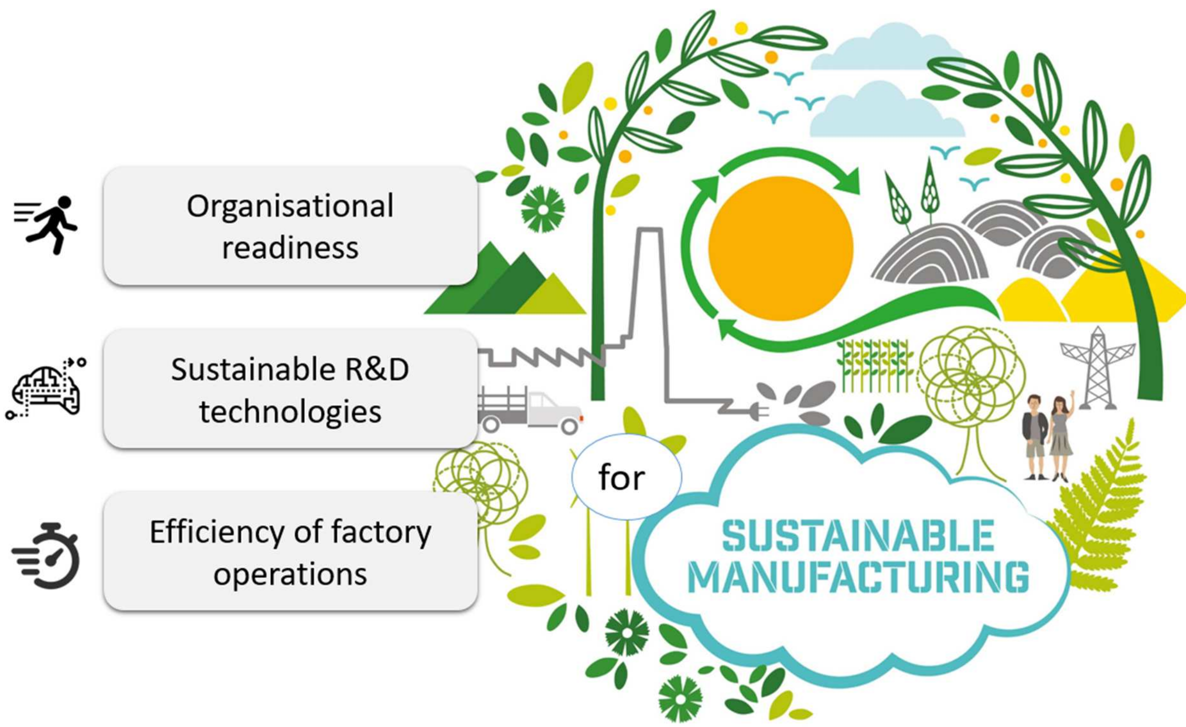
THESIS FOR THE DEGREE OF DOCTOR OF TECHNOLOGY

An Assessment Framework for Managing Corporate Sustainable Manufacturing

ILARIA BARLETTA



Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT
This research aims to support the manufacturing industry in the endeavour of achieving the seventeen sustainable development goals by 2030, with “sustainable production” (the 12th goal) being the key one it should achieve. The output of this research is synthesised into a framework comprising assessment methods and tools which translate both economic and environmental sustainability factors into information for a specific set of company management decisions. These decisions are supported by the three guiding functions of the framework: 1) alignment between sustainability strategy and operations through the definition of core organisational capabilities, 2) assessment of the environmental impacts of R&D technology for production systems, and 3) improvement of the sustainability performance of existing production systems’ operations. Thus, the framework encompasses sustainability assessment methods and tools from a low level of analysis (machine tool) to a higher one (organisational). For the first function, an organisational “sustainability readiness” tool was developed with six companies. For the second function, an indicator for environmental break-even analysis of R&D technologies aims to pre-emptively minimise any undesired backfire effects. For the third function, an energy-based version of the known overall equipment effectiveness indicator diagnoses energy inefficiencies in production. By highlighting a red thread between the three functions and by providing assessment solutions in each of them, the proposed assessment framework aims to support management in their task to measure sustainable manufacturing. The use of the framework would also mitigate the strategy-operations misalignment that sometimes affects corporate sustainability management. The overall qualitative nature of the framework makes it suitable to be considered by industrialists and academia as a conveyer of a mindset which leverages management’s capacity to improve sustainability performance. Unfortunately, the validity of this statement could not be tested. What has been validated to various extents though are the methods and tools within the framework itself. The author suggests that future research would enable manufacturing companies to quantify the long-term sustainability impacts of product life cycles and production systems. If this could be encouraged, it would help to focus on eco-effectiveness performance, perhaps by taking an approach similar to Science Based Targets. Interventions such as these can contribute to a safer future that remains environmentally accountable at all levels of business operations.

KEY WORDS: energy efficiency, environmental sustainability, key performance indicators, life cycle thinking, sustainability management, sustainable manufacturing, technology assessment

PREFACE

Can you picture what a *sustainable production system* looks like? Is it a clean environment surrounded by abundant greenery, operated by happy, well-adjusted workers and producing long-lasting, reusable products that add value to our lives? Whatever your personal take is currently, hold that image. After reading this dissertation, try this exercise again. As you visualise for the second time, I hope you will have a more enriched understanding of why it is critical that research be directed towards simplifying – or perhaps more aptly "decodifying"- such potentially confusing concepts for those who matter most –the decision makers in manufacturing management. Furthermore, I hope you will have a more enriched understanding what a sustainable production system can be, and, alternatively, at the very least, a less unsustainable one. To illustrate the potential breadth, a production system can be a production line with computerised mill machines that knows which product it will work on next, or might be comprised of two operators working next to conveyor belts installed for sorting operations of e-waste streams. When you arrived at your own version earlier, I am sure that certain concepts like zero waste, pollution prevention, and energy efficiency came to mind, at least in part. These concepts belonging to the realm of sustainability measurement and management, whilst deserving of their centrality in our collective consciousness, are, in my opinion, better placed in a broader framework of sustainability management that rightly tasks us with assessing such sustainability from the complete product-life cycle perspective. In truth, in order to demonstrate a genuine desire to achieve what we might loosely term "sustainability", it is necessary to appreciate the degree of nuance and complexity involved. Such unexamined facets could be included by the questions "what degree of sustainability is achieved via re-organising operations and processes rather than buying new equipment?" and "what are the potential adverse effects of creating such new technology?" Sustainability scholars, a growing number of common citizens as well as those managers driven by good will are already seeking answers to these questions. If you find yourself agreeing with the imperatives outlined above, then I encourage you to read on this doctoral dissertation. It is at times a long and far from perfect document. It proposes six assessment tools that have been validated in the industry with mixed results and unsolved gaps. The framework's greatest value lies in the link between strategy development, expressed by the definition of core organisational capabilities, production development through technology adoption and production operations' management through efficiency performance indicators. My hope is that, if implemented in Industrial practice, this framework will succeed in fostering true life cycle at every level of the organisation. In the end, my hope for this dissertation is that it will take us one step closer to the adoption and implementation of the vast body of sustainability-related theory already advanced. Whilst seeming to operate in the cracks of current discourse, my ultimate goal has been to bridge the gap between theory and application.

ACKNOWLEDGEMENTS

Finalising a PhD implies that the PhD candidate has been both the brain and the hand (actually, the typing fingers) of all the work that ends up in her thesis. However, there is a powerful, lymphatic infrastructure of people (leaders and followers alike), ideas, funding agencies and improvised motivational coaches that allow this mental and physical symphony to happen at all.

I would like to thank my supervisor, Professor Björn Johansson, for having affirmed me from the outset, as I explained my master thesis to him during my job interview: “there are so many interesting things to discuss”. Thank you Björn for welcoming me into your team and believing in me.

Thank you to my examiner Professor Johan Stahre for the constructive discussions at various points of my career as PhD student. Thanks also for sponsoring my podcast project, which made me feel even more connected with our great team.

Thank you Cessie (Assistant Professor Cecilia Berlin) for being a role model as a creative, energising teacher and the master of critical-feedback. I have learned a lot from your supervision.

Thank you Mélanie (Assistant Professor Mélanie Despeisse) for stepping in as my co-supervisor in the last year of my PhD. Your enthusiasm for sustainability research has been contagious, for both me and the group you are building. Arpita, Clarissa and Xiaoxia, I am happy to have met you.

I thank my opponent Steve Evans, and the members of my grading committee: Christina Claeson-Jonsson, Elina Huttunen-Saarivirta, Henrikke (Kikki) Baumann, and Sebastian Thiede. Thank you for such an active and attentive reading of my thesis. When it was still at draft stage, you all raised points that activated fresh modes of thinking that would have otherwise been suppressed by the necessary autopilot of such a great undertaking. I really look forward to discussing with you all.

A mention is due to the funding agencies for which I carried out my research work: Vinnova, EU Interreg Baltic Sea Region, Horizon 2020 EU, and EIT Climate KIC.

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Thank you to the company project partners I worked with in Australia and the EU – Sweden in particular. You opened the doors of your offices and factories for me and shared your knowledge with me.

I dedicate this work to my mother Anna and my father Mario. You both have always been there for me. You understood every struggle and participated in every joy without the need for knowing any of the details of my work. This is an example of what love realises.

I dedicate this work also to my partner Matthew: we have been 16000 kilometres apart for most of my time as PhD student. You have always encouraged me to be the best version of myself, to see every day as a new opportunity to grow, and every challenge or setback as a potential opportunity. Thank you for shining that unique light of joy and love to everybody around you.

To my best friend Stella: I cannot imagine having a conversation with you and not feeling 100% absorbed and involved. You intriguing hybrid of "fortune teller", fashion addict, entrepreneur, and dog lover are an important part of my life, and you will always be.

To my brother Piero and sister in law Susanna, and my relatives, in particular aunt Rosaria, aunt Luciana, uncle Francesco, and aunt Eleonora, and my cousins, in particular Tonia and Matteo (Teo). Thanks Teo for helping me with the podcast production.

Thanks to the members of the self-proclaimed, self-organised *Science Lounge* discussion group: Cessie, Eva, Lars-Ola, and Magnus. The Science Lounge has been the best conversational gym I have ever joined.

Thanks to my colleagues Jonatan, Maja, and Malin, amusing writing buddies. Thanks to all my colleagues who shared stories, smiles and advice with me.
Thanks to the students whom I supervised for their Bachelor or Master Thesis projects. It was a pleasure to learn from you.

RINGRAZIAMENTI

Quando una dottoranda porta a termine il suo dottorato significa che tutto quello che c'è nella sua tesi è il risultato dell'azione coordinata del suo cervello e delle sue braccia (anzi, dita che picchiano forsennatamente una tastiera). Ciononostante, come sappiamo, esiste un'infrastruttura linfatica di persone (sia leader che follower), idee, enti di sovvenzionamento alla ricerca e motivational coaches improvvisati che permettono alla dottoranda di far funzionare braccia e cervello in maniera appropriata.
Voglio ringraziare il mio supervisor, il Professore Björn Johansson, per aver detto, durante il mio colloquio di lavoro, quando illustravo i risultati della mia tesi "ci sono così tante cose interessanti da discutere". Grazie di avermi accolto nel tuo team e aver creduto in me.

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APPENDED PAPERS – CORE PUBLICATIONS

Seven papers were deemed “core publications”, which is to say they strongly supported the conclusions of the research. These are listed chronologically, starting with the earliest publication date.

Paper I:
Barletta, I., Andersson, J., Johansson, B., May, G. and Taisch, M., 2014, December. Assessing a proposal for an energy-based overall equipment effectiveness indicator through discrete event simulation. In Proceedings of the Winter Simulation Conference 2014 (pp. 1096-1107). IEEE.

Contribution:
Ilaria Barletta developed the indicators, determined the key design of the simulation model and experiments and managed the data analysis. She was also principal author of the manuscript.

Paper II:
May, G., Barletta, I., Stahl, B., and Taisch, M. 2015. Energy Management in Production: A novel Method to Develop Key Performance Indicators for Improving Energy Efficiency. *Applied Energy, 149,* pp. 46-61.

Contribution:
Ilaria Barletta designed the method, conducted the literature study and analysed one of five case studies. She co-authored the manuscript.

Paper III:
Barletta, I., Larborn, J., Mani, M. and Johansson, B., 2016. Towards an Assessment Methodology to Support Decision Making for Sustainable Electronic Waste Management Systems: Automatic Sorting Technology. *Sustainability*, 8(1), p.84.

Contribution: Ilaria Barletta designed the method and conducted data collection and data analysis activities. She was principal author of the manuscript.

Paper IV:

Rebouillat, L., Barletta, I., Johansson, B., Mani, M., Bernstein, W.Z., Morris, K.C., and Lyons, K.W. 2016. Understanding Sustainability Data through Unit Manufacturing Process Representations: A Case Study on Stone Production. *Procedia CIRP, 57*, pp. 686-691.

Contribution: Ilaria Barletta was lead supervisor of the research relating to the literature to review and principal analysis methods used. She also co-authored the manuscript.

Paper V:

Barletta, I., Berlin, C., Despeisse, M., Van Voorthuysen, E. and Johansson, B., 2018. A Methodology to Align Core Manufacturing Capabilities with Sustainable Manufacturing Strategies. *Procedia CIRP, 69*(1), pp.242-247.

Contribution: Ilaria Barletta developed the methodology, conducted data collection and data analysis activities and was principal author of the manuscript.

Paper VI:

Barletta, I., Despeisse, M. and Johansson, B., 2018. The Proposal of an Environmental Break-Even Point as Assessment Method of Product-Service Systems for Circular Economy. *Procedia CIRP, 72*(1), pp.720-725.

Contribution: Ilaria Barletta adapted the methodology from previous research, conducted data collection and data analysis activities and was principal author of the paper.

Paper VII:

Barletta, I., Despeisse, M., Hoffenson, S., Mani, M., and Johansson, B. (-) An Organisational Sustainability Readiness Tool for Manufacturing Companies. Submitted to *Business Strategy and the Environment.*

Contribution:

Ilaria Barletta developed the tool, conducted data collection and data analysis activities and was principal author of the manuscript.

APPENDED PAPERS - ADDITIONAL PUBLICATIONS

Five papers were deemed “additional publications”, as they did not offer relevant support to the conclusions of the research, but were instrumental in improving the author’s research skills and contributed to a broader understanding of her research field. These papers are listed chronologically, starting with the earliest publication date.

Paper VIII:

Barletta, I., Johansson, B., Reimers, J., Stahre, J. and Berlin, C., 2015. Prerequisites for a high-level framework to design sustainable plants in the e-waste supply chain. *Procedia CIRP, 29*, pp.633-638.

Contribution:

Ilaria Barletta designed and implemented the framework in a case study. She conducted data collection and analysis and was principal author of the manuscript.

Paper IX:

Taghavi, N., Barletta, I. and Berlin, C., 2015, September. Social implications of introducing innovative technology into a product-service system: The case of a waste-grading machine in electronic waste management. In *IFIP International Conference on Advances in Production Management Systems* (pp. 583-591). Springer, Cham.

Contribution:

Ilaria Barletta designed the case study, was responsible for some of the data collection activities and co-authored the manuscript.

Paper X:

Berlin, C., Barletta, I., Fantini, P., Georgoulias, K., Hansich, C., Lanz, M., Latokartano, J., Pinzone, M., Schönborn, G., Stahre, J. and Taisch, M., 2016. Prerequisites and Conditions for Socially Sustainable Manufacturing in Europe’s Future Factories—Results Overview from the SO SMART Project. In *Advances in Ergonomics of Manufacturing: Managing the Enterprise of the Future* (pp. 319-330). Springer, Cham.

Contribution:

Ilaria Barletta supported the (workshop-led) data collection activities and some data analysis activities arising from the workshops. She co-authored the manuscript.

Paper XI:

Whalen, K.A., Berlin, C., Ekberg, J., Barletta, I. and Hammersberg, P., 2018. ‘All they do is win’: Lessons learned from use of a serious game for Circular Economy education. *Resources, Conservation and Recycling, 135*, pp.335-345.

Contribution:

Ilaria Barletta led one of the cohort studies, coded and analysed a portion of the textual data and co-authored the manuscript.

Paper XII:

Pinzone, M., Albè, F., Orlandelli, D., Barletta, I., Berlin, C., Johansson, B. and Taisch, M., 2018. A framework for operative and social sustainability functionalities in Human-Centric Cyber-Physical Production Systems. *Computers & Industrial Engineering*.

Contribution:

Ilaria Barletta supervised the research work, co-authored two chapters of the manuscript and contributed to its overall review.

GLOSSARY

This list reports definitions of terms that are needed to contextualise this research.

Term	Definition
Business performance measurement	“From an operations perspective, a business performance measurement system is mainly perceived as a “set of metrics used to quantify both the efficiency and effectiveness of actions” (Neely et al., 1995) as per reported by (Franco-Santos et al., 2007).
Decision making	“Decision making can be defined as choosing a particular option from multiple alternatives, and it is often carried out in order to maximize certain desirable quantity, such as reward or utility” Lee (2009).
Environmental impact	“…the extent to which certain actions change availability of certain resources or energy in the environment or alter certain structures and dynamics of ecosystems” (Kopnina and Blewitt, 2014).
Framework	“…refers to the active employment of particular sets of recommendations: for example, a set of measurement recommendations may suggest the development of a structural framework …or they may give rise to a procedural framework...”(Folan and Browne, 2005).
Key performance indicator	“Key performance indicators (KPIs) are fundamental in measuring the performance and its progress. [In manufacturing, *author’s note*] KPIs can provide information about the performance in different areas such as energy, raw-material, control & operation, maintenance, planning & scheduling, product quality, inventory, safety, etc.” (Lindberg et al., 2015).
Life cycle assessment	“…a comprehensive, standardised and internationally recognized approach for quantifying all emissions, resource consumption, related environmental and health impacts linked to a service, asset or product “ (Du, 2015) elaborating from (Treloar et al., 2000, ISO 14040, 2006, ILCD, 2010).
Management (activity)	“The organisation and coordination of the activities of a business in order to achieve defined objectives” (Business Dictionary, 2019a).
Management (people)	“The directors and managers who have the power and responsibility to make decisions and oversee an enterprise” (Business Dictionary, 2019a).
Management control systems	“Management control systems provide information that is intended to be useful to managers in performing their jobs and to assist organisations in developing and maintaining viable patterns of behaviour” (Otley, 1999)

Term	Definition
Organisation	“A social unit of people that is structured and managed to meet a need or to pursue collective goals. All organisations have a management structure that determines relationships between the different activities and the members, and subdivides and assigns roles, responsibilities, and authority to carry out different tasks…” (Business Dictionary, 2019b).
Performance indicator	“A performance indicator is a variable indicating the effectiveness and/or efficiency of a part or whole of the process or system against a given norm/target or plan ” (Fortuin, 1988).
Performance management system	A performance management system is “concerned with defining, controlling and managing both the achievement of outcomes or ends as well as the means used to achieve these results at a societal and organisational, rather than individual, level” (Broadbent and Laughlin, 2009).
Stakeholders	“Any group or individual who can affect or is affected by the achievement of the organisation's objectives” (Freeman, 1994).
Sustainable development	“The development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (The World Commission on Environment and Development, 1987).
Sustainability	“The quality of being able to continue over a period of time” (Cambridge Dictionary, 2019a).
Sustainability impacts	“The social, economic and environmental impacts [in a Life Cycle Sustainability Assessment (LCSA)] are characterized by a set of impact categories and their respective performance indicators. In (ISO 14040, 2006) an impact category is defined as a “class representing environmental issues of concern to which life cycle inventory analysis results may be assigned”. For LCSA, this definition is extended to social and economic issues ”(Souza et al., 2015). *Author’s note*: this definition assumes that sustainability is seen as corporate triple bottom line: in other words, economic, environmental and social sustainability (Elkington, 1997).
Sustainable consumption and production	“Sustainable consumption and production refers to the use of services and related products, which respond to basic needs and bring a better quality of life while minimising the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the life cycle of the service or product so as not to jeopardize the needs of future generations” (UN Environment).
Technology	“(The study and knowledge of) the practical, especially industrial, use of scientific discoveries” (Cambridge Dictionary, 2019b).

ABBREVIATIONS

e-BEP	Environmental breakeven point
CNC	Computer numerical control
DES	Discrete event simulation
e-KPI	Energy-related key performance indicator
Eq.	Equation
GDP	Gross domestic product
ICT	Information and communication technology
KPI	Key performance indicator
LCA	Life cycle assessment
LCE	Life cycle engineering
NIST	National institute of standards and technology
OECD	Organisation for economic co-operation and development
RQ	Research question
SDG	Sustainable development goal
RBV	Resource based view
UMP	Unit Manufacturing Process
UN	United Nations
WEEE	Waste of electrical and electronic equipment

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FIGURES

TABLES

1. Introduction

"If you do not ask the right questions, you do not get the right answers. A question asked in the right way often points to its own answer. Asking questions is the A-B-C of diagnosis. Only the inquiring mind solves problems."

Edward Hodnett (1901 - 1984)
Author

1.1. The role of the manufacturing sector in the sustainability challenge

Manufacturing parallels human history from its early days. Homo erectus manufactured the first primitive stone implements as far back as 1.7 million years ago (Diez-Martín et al., 2015, The Editors of Encyclopaedia Britannica, 2016). The raw materials needed for procuring such tools were in ready abundance for our ancestors and their sparsely populated habitat. Today though, in a world of 7.6 billion people, we consume resources at a rate aligned with what 1.7 Earths would offer (Global Footprint Network). The consequences of such consumption rates are frightening in view of a predicted global population of 9.8 Billion by 2050 (United Nations, 2017). Four out of the nine planetary boundaries[1] that define Earth's carrying capacity have already been crossed (Steffen et al., 2015), such as biosphere integrity and climate change. In 2016, CO_2 emissions from direct industrial energy use reached 8.3 GtCO2, or 24% of global energy emissions (International Energy Agency). Can we maintain a safe operating space and yet exercise our ability to create artefacts for our needs of safety, belonging and participation? The United Nations (UN) provided a goal-based answer to the above question. In 2015, the UN issued its 17 sustainable development goals (SDGs)[2]. Each of them is part of a development agenda for the world's countries and their economies by 2030. The 12th of

[1] The nine planetary boundaries are: 1) Stratospheric ozone depletion, 2) loss of biosphere integrity, 3) chemical pollution and the release of novel entities, 4) climate change, 5) ocean acidification, 6) freshwater consumption 7) land system change 8) Nitrogen and phosphorus flows to the biosphere and oceans, and 9) Atmospheric aerosol loading. The planetary boundaries being crossed are #nos .2, 4, 7 and 8.

[2] The SDGs are: 1) No poverty 2) Zero hunger 3) Good health and wellbeing 4) Quality education 5) Gender equality 6) Clean water and sanitation 7) Affordable and clean energy 8) Decent work and economic growth 9) Industry, innovation and infrastructure 10) Reduced inequalities 11) Sustainable cities and communities 12) Responsible consumption and production 13) Climate action 14) Life below water 15) Life on land 16) Peace justice and strong institutions 17)Partnerships for the goals.

these SDGs is "responsible consumption and production". Obviously, the manufacturing industry will be one of the chief planners and executors of this goal.
In the European Union, the manufacturing sector's contribution to national value added (as a percentage of GDP) is 21.9%. Similarly, for heavily indebted poor countries, the contribution totals 22.6% (The World Bank). It therefore follows that sustaining the manufacturing sector is key for both developed and developing countries. The question then is: what does the future path of the manufacturing sector look like?

1.2. Sustainable manufacturing

There is no consensus yet on the definition of sustainable manufacturing (Moldavska and Welo, 2017). Arguably, this is for the same reasons that it is hard to get consensus on a definition of sustainable development. However, the US Department of Commerce's definition (International Trade Administration, 2007) stands out as most-cited in the literature (Moldavska and Welo, 2017).
In this research, sustainable manufacturing comprises the set of transformation processes and related supporting business processes which realise a product according to three principles:

1. Ecological: not causing sustainable nature's functions and diversity to be systematically impoverished, or subject to increasing concentrations of substances produced by society and extracted from the Earth's crust.
2. Economic: guaranteeing long-term profitability of the supply-chain which realises the product.
3. Social: contributing to the wellbeing of employees, product users and affected local communities.

The above definition incorporates the principles of The Natural Step into the "traditional" definition of sustainable manufacturing (Robèrt et al., 1997, The Natural Step, 2018). These relate to ecological sustainability and the construct of well-being, both of which relate to social sustainability. Moreover, the term "customer", which used to appear in its traditional definition, has been replaced by the term "user". Sustainability, in the context of manufacturing, does not relate to the extent to which the business-as-usual scenario is sustained with the least financial effort. Rather, sustainability is the extent to which manufacturing companies are able maintain the conditions they control and which realise the 2030 Agenda. Preceding such a state are the interventions of the *unsustainability* challenge.

1.3. Vision and aim of the research

This research was inspired by a vision of a future sustainable manufacturing industry.

> ***Vision***
>
> Manufacturing companies have successfully contributed to reach the seventeen sustainable development goals and shaped a new paradigm of competitiveness, grounded on the fulfilment of the principles of sustainable manufacturing. Maintaining this paradigm is what must be sustained.

Realising this vision entails a dramatic change in the way contemporary manufacturing companies do business. Since this research focuses on sustainability at a corporate (individual company) level, key aspects of interest are assessing sustainability-related performance and sustainability impacts of the company's core business (in this case, manufacturing). Moldavska and Welo (2018) defined a corporate sustainability assessment as "a branch of sustainability assessment to evaluate organisational performance and assist decision-makers in determining which actions should or should not be taken in an attempt to contribute to sustainable development". Paju et al. (2010) and Raoufi et al. (2017) highlighted two reasons for putting sustainability assessment at companies' fingertips. Firstly, tools for sustainability assessment from applied research may not be easily accessible to industry. Secondly, if tools are available, manufacturing companies may not have the necessary competences to carry out sustainability assessments (**gap 1**). Consequently, the aim of this research is:

> ***Aim***
>
> Develop an assessment framework for sustainable manufacturing to make corporate management understand how to positively influence relevant economic and environmental sustainability performance.

1.4. Research questions

Pursuing this aim relies on the following assumption: manufacturing companies will increase their ability to achieve the goal of sustainable and responsible production when management utilises goal-relevant information from performance and impact indicators.

Despite the rapid transformation of production systems driven by Industry 4.0 (Monostori, 2014) and circular economy business models (Lieder and Rashid, 2016), it was apparent that only a small number of scientific publications were focused on changes in "brownfield" production systems and manufacturing plants from a sustainability perspective.

Indeed, alongside the prevailing strong emphasis on product design and re-design, Jayal et al. (2010), Rödger et al. (2016), and Ahmad and Wong (2018) called for equal emphasis on processes and production systems if manufacturing companies are to address all the three pillars of sustainability (Elkington, 1997) (**gap 2**).
Consistent with the aim of this research, this gap resulted in the development of the first research question (RQ1).
RQ1: How can manufacturing companies integrate economic and environmental sustainability factors into their production systems, both in the development and in the operations phases?

If RQ1 is answered, the scope of analysis can then be expanded to the organisational level whilst still examining production operations and how they are assessed from a sustainability perspective.

The "missing link" between manufacturing strategy and manufacturing operations has been previously discussed by such academics as Skinner (1969), Wheel Wright (1984) and Hayes and Pisano (1994). The topic also comprised sustainability-focused business research, with the work of Bonn and Fisher (2011) and Amini and Bienstock (2014), among others. Most recently, Satyro et al. (2017) claimed that attention has yet to be given to the strategy-formulation process for environmental sustainability. Furthermore, the consultancy McKinsey & Co. advocated that "executives should develop sustainability strategies with the same rigor they use to develop their business strategy and with the overall business strategy in mind" (McKinsey & Co, 2017). It follows that companies need support in formulating and developing sustainability strategy and, arguably, aligning it with operations (**gap 3**).
This researcher hypothesizes that one of the ways to provide such support is by addressing the strategy-operations alignment in manufacturing companies that aim to be considered "sustainable". This gap resulted in the development of the second research question (RQ2).
RQ2: How can manufacturing companies align their operations with their corporate sustainability strategy?

The two research questions (RQs) are illustrated below:

RQ1: How can manufacturing companies integrate economic and environmental sustainability factors into their production systems, both in the development and in the operations phases?

RQ2: How can manufacturing companies align their operations with their corporate sustainability strategy?

RQ1 and RQ2 suggest that this research works in the interplay between two fields: the engineering field of sustainable manufacturing on one side, and the business field of corporate sustainability on the other. The former is more prominently investigated in RQ1, whereas the latter is more prominently investigated in RQ2.

1.5. Target audience of this research

The target audience of this research lies in two groups: the manufacturing industry and academia.
The industry-based target is illustrated in Figure 1 in the red rectangles.

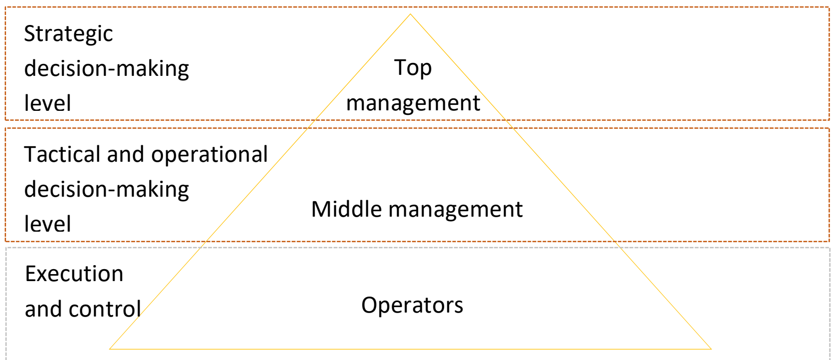

Figure 1: Decision-making level of the target audience in the manufacturing industry.

At the highest level in Figure 1, there are manufacturing executives motivated to align their business with the SDGs. At the intermediate level of manufacturing, there are middle-management people who want to incorporate sustainability factors into operational decisions (such as quality control and production scheduling) and into sustainability-management toolboxes (such as key sustainability performance indicators and balanced sustainability scorecards).
The academia portion of the target audience consists of scholars specialised in theory development and tool development in sustainable manufacturing, industrial sustainability, and corporate sustainability, with a particular focus on performance assessment and management. They provide knowledge to support and direct the theoretical development and validation of this research.

1.6. Research delimitations

This section lays out the delimitations of this research. These are expressed in terms of research or application areas beyond the scope of our investigation into developing an assessment framework. The excluded research areas are:

- process industry;
- social sustainability performance and social impacts. However, studying social sustainability *aspects* and *implications* may still play a role in the answer of the RQs;
- sustainable supply chain management in manufacturing supply chains;
- decision-making at a product design and product development level in manufacturing (such as eco-design);
- cause-effect relationships between economic and environmental performance areas;
- leadership and organisational behaviour for corporate sustainability (such as organisational culture, ethical corporate identity, employee green behaviour);
- business models for sustainable manufacturing (such as product service systems, circular economy business models).

The theoretical framework that defines and describes the body of knowledge included in the research is instead presented in Chapter 2.

1.7. Research process

Figure 2 illustrates the process as a timeline, running from the inception of the enquiry until the validation of results.

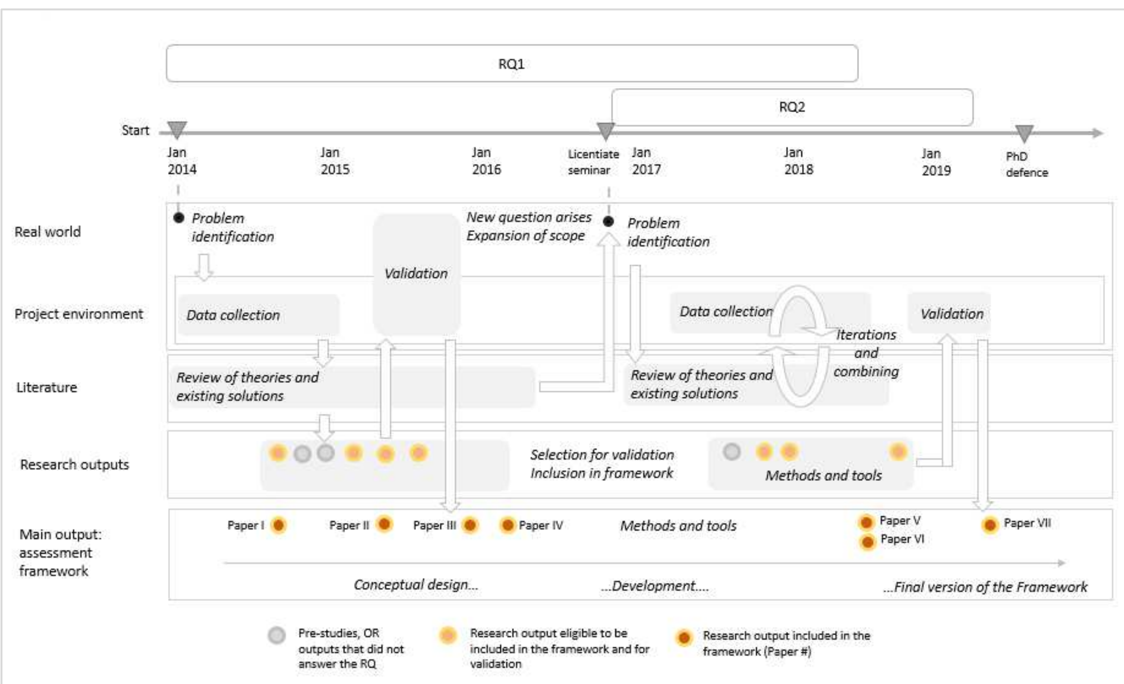

Figure 2: Research process timeline.

1.8. Document outline

Figure 3 outlines this document. It also shows the connections between chapters and the sequential connections from Chapter 1 to Chapter 6.

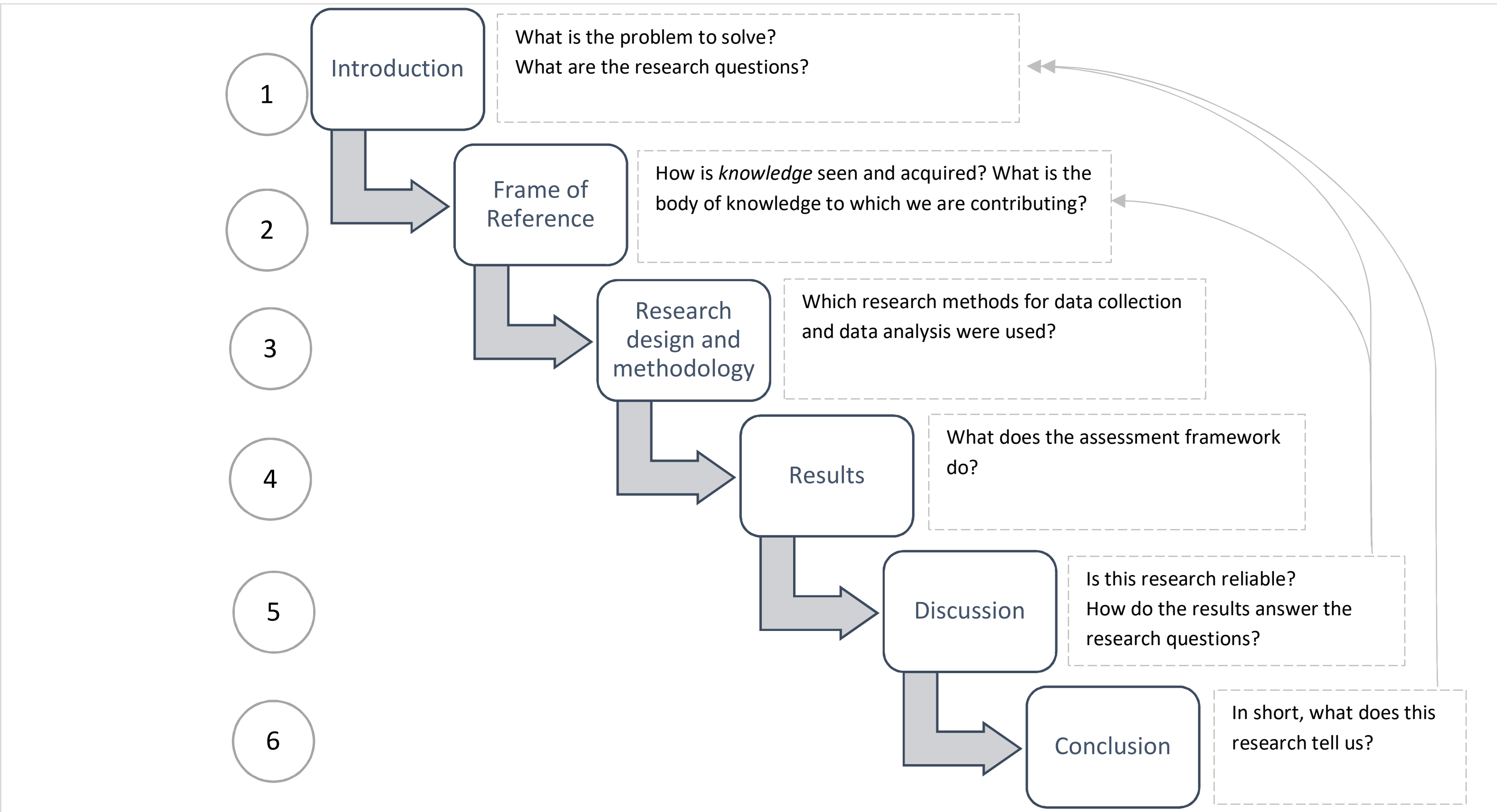

Figure 3: Outline of this PhD-thesis report and the questions each chapter aims to answer.

2. Frame of reference

The only way of discovering the limits of the possible is to venture a little way past them into the impossible

Arthur C. Clarke, (1917-2008)
Science fiction writer

This chapter starts with an explanation of the philosophical worldviews being adopted (Section 2.1). Section 2.2 illustrates the theoretical framework of this research. Section 2.3 highlights the gaps in the relevant body of knowledge.

2.1. Philosophical worldviews

In the context of a doctoral thesis, the term “worldview” indicates what Guba (1990) defined “a basic set of beliefs that guide action”. As Creswell (2009) pointed out, other scholars used terms such as “paradigms”(Mertens, 2010, Lincoln et al., 2011) and “epistemologies and ontologies” (Crotty, 1998). During the five-year term of this research, this researcher observed, in retrospect, an intriguing evolution in the various worldviews exhibited. Figure 4 illustrates these on a timeline.

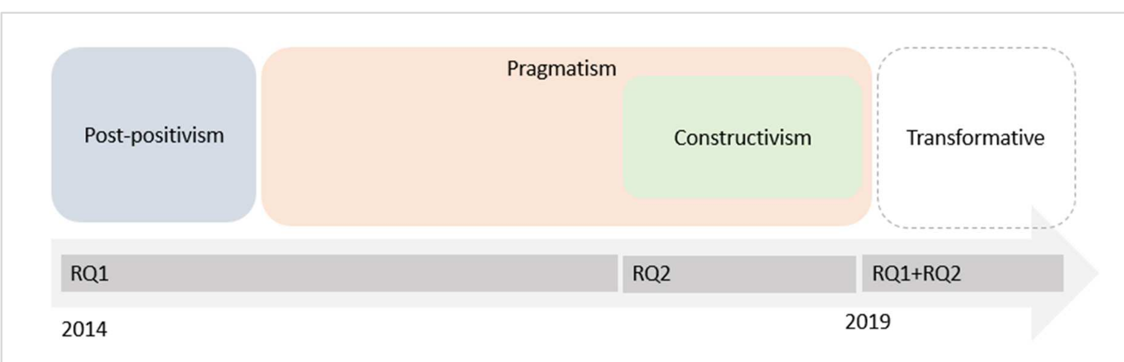

Figure 4: Worldviews adopted in this research, their timeline and reference to the RQs

Figure 4 shows an "epistemological" evolution from a deterministic and reductionist view (dating back to 2014) to a future transformative and change-oriented view applied to what this researcher now calls "sustainable manufacturing".

The post-positivist period (2014-2015)

At the beginning of this research, in 2014, sustainable manufacturing acquired a meaning almost coinciding with a simple concept of energy efficiency in production and, to a broader extent, operational efficiency. This worldview corresponds to post-positivism, a deterministic and reductionist approach to the creation of scientific knowledge originating from thinkers such as Mill and Locke (Smith, 1983a), and most recently Phillips and Burbules (2000). A post-positivist worldview was actually adopted in 2015. At that time, sustainability impacts were measured, but with no particular investigation of whether measuring sustainability through a preselected set of indicators was a comprehensive answer to the research questions.

The pragmatism period (2015-2019)

Being involved in multiple research projects resulted in three key realisations:

1. Urgency to produce practice-oriented assessment tools to solve the targeted problem.
2. Pluralistic conceptualisation and operationalisation of sustainable manufacturing, by academics as well as corporate management (which each face different realities and develop different positions on sustainability).
3. Openness in adopting various different research methods to solve the targeted problem (also due to point 2).

These realisations ascribe to what is called "pragmatist worldview", which derived from the ideas put into words by Pierce, Mead, James and Dewey (Cherryholmes, 1992).

The constructivist period (2016 – 2018)

As more interactions with management in manufacturing companies took place, this researcher realised that if the aim of her research was to be achieved, a systematic understanding of how executives and middle management discuss sustainable manufacturing would have to play a critical role. Thus, comprehending how the concept of sustainable manufacturing was understood by industry was crucial to understanding how sustainability assessment tools could be a "success factor" or not. Although this realisation did not lead to ethnographic studies or discourse analyses, it nevertheless motivated a shift in the research approach. There was a renewed focus on open-ended questions and, naturally, qualitative data. This worldview is defined as "[social] constructivism" and was illustrated by Lincoln and Guba (1985) and then described by Crotty (1998) and Mertens (2010).

The transformative period (2019 –)

According to Creswell (2009), a transformative worldview entails "an action agenda for reform that may change lives of the participants, the institutions in which individuals work or live, and the researcher's life". This worldview was not openly declared in any of the research studies being conducted, as it emerged indirectly as a desirable future epistemological step in the research but at a time when the research projects' activities were already "frozen" and approaching finalisation. This researcher argues that a transformative view towards conducting future research (as action research) would reap greater benefits if applied to manufacturing companies deliberately seeking a change in how they operate (as compared to adopting a pragmatic and constructivist worldview, and, naturally, a post-positivist worldview).

2.2. Theoretical framework

The theoretical framework encompasses core concepts and relevant theories that ground this research and define its limit. Figure 5 displays the theoretical framework of this research.

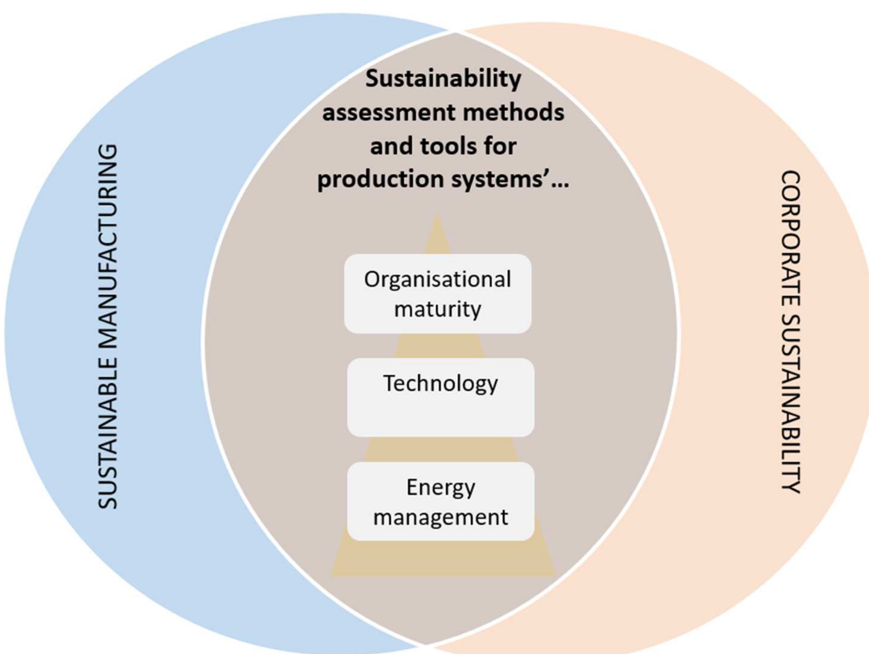

Figure 5: Theoretical framework. The focus area is at the intersection of the two circles. White boxes are areas where management needs support via solutions for sustainability assessment.

With reference to the elements of Figure 5, this section starts with an account of the top two fields of interest of this research: sustainable manufacturing and corporate sustainability. The intersection of these two fields is the focus area which was further investigated: *sustainability assessment methods and tools*. They were this researcher's chosen means of investigation to answer her RQs. Instantiations of sustainability assessment tools deemed suitable for answering RQ1 and RQ2 were: *energy efficiency assessment* (RQ1), *technology assessment* (RQ1) and *organisational maturity assessment* (RQ2). In reference to Figure 5, energy efficiency assessment supports effective energy management. Technology assessment may support the adoption of technologies that bring positive sustainability impacts at the product life cycle level. Organisational maturity assessment may support increased "maturity" of an organisation with respect to sustainability management. Figure 5 suggests that the three assessment tools (energy efficiency assessment, technology assessment and organisational maturity assessment) support decisions taking place at distinct hierarchical levels of the organisation. Energy efficient assessment is used at the operational level, technology assessment is used at the tactical level, and capability assessment is used at the strategic level.

In this research, sustainable manufacturing and corporate sustainability are understood from the perspective of systems engineering. The resource-based view of the firm is the theory used to observe corporate sustainability. Life cycle engineering is the approach used to analyse the field of sustainable manufacturing. These concepts will be introduced in the subsequent paragraphs.
The rationale behind the selection these particular areas of contribution via method/tool development came from the identification of specific gaps in the scientific literature. Corporate cases studied in prior research projects either confirmed specific research needs that were also present in the literature, or highlighted new opportunities for supporting sustainability management in production systems. The interaction between theory and empirics from the research design is presented in Chapter 3, with particular reference to Figure 9 on page 36 and its narrative.

2.2.1. Key concepts

Sustainable manufacturing

In this research, sustainable manufacturing as research field focuses on transformation processes occurring in production systems, given the definition provided on page 2. Another concept found in the academic discourse which overlaps with sustainable manufacturing is *industrial sustainability*. This refers to the "end state of a transformation process where industry is part of, and actively contributing to, a socially, environmentally and economically sustainable planet" (Tonelli et al., 2013). Dornfeld (2012) zooms in on the environmental pillar of sustainable manufacturing (*green* manufacturing) by summarising the knowledge on metrics and principles that instantiate green manufacturing on the machine-tool, production-system and supply-chain levels. This thesis still refers to the definition of sustainable manufacturing on page 2. A fuller picture of the solutions provided by the most prominent scholars in the sustainable manufacturing field will be given, once the disciplines inherent in their work are clarified.

Systems engineering

In this work, the lenses through which the unsustainability of the manufacturing industry is observed come from the discipline of systems engineering (Blanchard, 2004, Sage and Rouse, 2009). Firstly, according to Blanchard (2004) "a system is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies and documents; that is, all things required to produce system-level results". From a process viewpoint, a production system (such as an assembly line, or flexible manufacturing cell) is of interest to this research. Figure 6 illustrates the production system from a system-theory perspective, in which transformational processes occur in a black box, converting inputs to outputs.

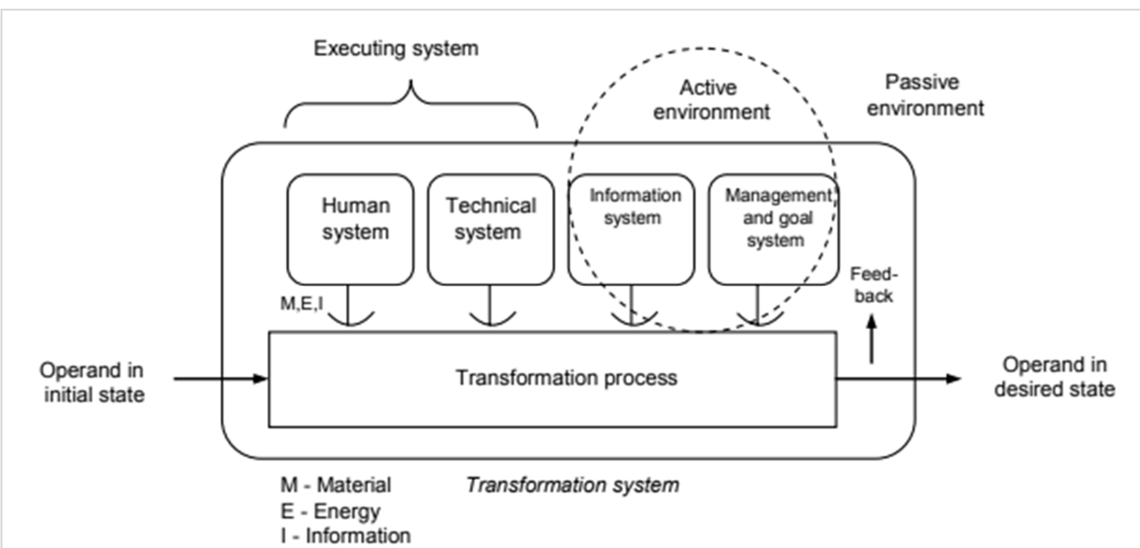

Figure 6: The production system as a transformation system, from Hubka and Eder (1988) as illustrated by Bellgran and Säfsten (2010).

Switching to an organisational viewpoint, manufacturing companies are also systems of interest for this research. Indeed, these two systems operate transformation processes to produce products and services (albeit on different scales). Such transformation processes impact the functioning of ecosystem services (such as water provision, removal of CO2 from the atmosphere) and wellbeing in human systems (employees, product users, communities and so on).

Systems engineering provides a valuable analytical perspective when it comes to the challenge of making the manufacturing industry sustainable. Indeed, the purpose of systems engineering is "information and knowledge organisation and management to assist clients[3] who desire to develop policies for management, direction, control and regulation activities relative to forecasting, planning, development, production and operations for total systems to maintain quality, integrity and integration as related to performance, trustworthiness, reliability, availability and maintainability" (Sage and Rouse, 2009).

Given the aim of this research, a key system-level result which must be guaranteed is sustainability. Hence, in this research, sustainability is the stability of a set of conditions ensuring that a manufacturing company can continue operating without hampering the achievement of the sustainable development goals (2030 Agenda) and which preserve the desired post-goal achievement state.

Life cycle engineering

A methodological approach which belongs to the theoretical framework of this research is life cycle engineering (LCE). LCE has been defined as "engineering activities which include the application of technological and scientific principles to manufacturing products with the goal of protecting the environment, conserving resources, encouraging economic progress, keeping in mind social concerns, and the need for sustainability, while optimizing the product life cycle and minimizing pollution and waste"(Jeswiet, 2014).

In this research, LCE encompasses production development and operations management at factory level, where the product is "a given" and the production system has technological and managerial variables which can be manipulated for increased economic and environmental performance.

Hence, in this work, the "object" which has a life cycle is not just the product, but also the production system. Wiktorsson (2000) gave what is now an established illustration of the life cycle of a production system (Figure 7 on the next page).

[3] In this case, "clients" are manufacturing companies.

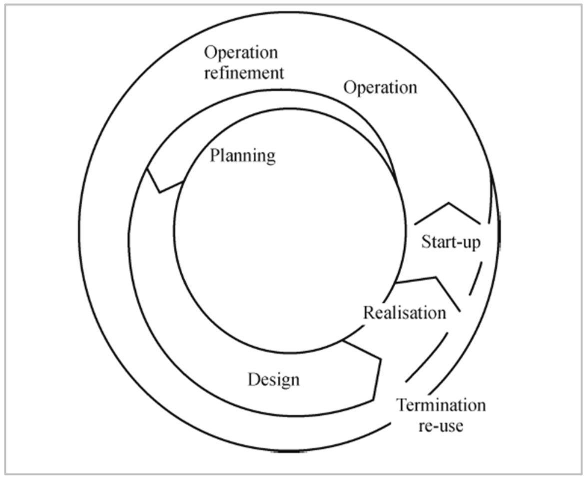

Figure 7: Life cycle phases of a production system, from Wiktorsson (2000).

“Operation refinement” indicates a process of change or upgrade of an existing production system, which was broadly and conveniently named “production development” in RQ1. This research supports decisions at the operations level and operation refinement level of production systems. This is because it investigates potential changes, at either a technological or managerial level, to existing production systems.

Corporate sustainability

Corporate sustainability is defined as “corporate activities that proactively seek to contribute to sustainability equilibria, including the economic, environmental, and social dimensions of today, as well as their inter-relations within and throughout the time dimension while addressing the company’s[4] system (including operations and production, management and strategy, organisational systems, procurement and marketing, and assessment and communication); and its stakeholders” (Lozano, 2012).

In grouping different areas of corporate sustainability, Lozano (2012) isolated studies by a number of authors who had defined theoretical aspects upon which the present research has drawn. In particular, in operations and production, Lozano (2012) included corporate sustainability which was dedicated to closed-loop manufacturing and combined with resource efficiency and effectiveness. In their overview, Lorenzi and Riley (2000) described it from the perspective of change management. However, this has not been the perspective adopted in this research.

A further area within corporate sustainability (and relevant to this research) covers organisational systems which, according to Lozano (2012), include “people, culture,

[4] The term “company” has been considered equivalent to “firm” in this research. There is a difference between “company” and “firm” in terms of legal liabilities, but this research deems the difference negligible as weighing legal aspects is beyond its scope.

leadership styles, management skills and learning, problem-solving approaches, structures, systems". Given the delimitations of Section 1.6, only management systems and problem-solving approaches fall within scope of this research.

Strong sustainability vs weak sustainability

Any given definition of sustainability and sustainable development (and their derivatives) such as "sustainable manufacturing", are value-laden (Kates et al., 2005, Kemp and Martens, 2007).

In this context, values are defined as "expressions of, or beliefs in, the worth of objects, qualities, or behaviour" (Kates et al., 2005). The fact that a divide exists between "strong sustainability" and "weak sustainability" (Gowdy, 2001, Neumayer, 2003, Pearce, 2014) demonstrates the fact that different sustainability-related definitions stem from different value systems. They inevitably echo sustainability goals and indicators, or the lack thereof (Kates et al., 2005). Such a difference results in different outputs and outcomes occurring when transforming sustainability from concept to measurement, aka, in the passage from contextualisation to operationalisation (Briassoulis, 2001).

This research recognised but did not categorise all the different value systems which dictate how sustainability is operationalised.

Resource-based view of the firm

Lozano et al. (2015) presented a critical overview of how well-known theories of the firm (Stockholder Theory, Stakeholder Theory, Aggregate Theory, Contractual Theory, Resource Based View Theory) have been applied to corporate sustainability. Of those theories, the resource-based view (RBV) (Wernerfelt, 1984) is the one underpinning this research. RBV sees a firm as a collection of productive resources, which, if properly managed, lead to an increased ability to compete. On top of the obvious tangible resources which a company manages, such as plant, equipment, land, natural resources, employees, and so on, Sanchez and Heene (1997) added intangible resources, that is, capabilities and cognitions (Lozano et al., 2015).

The selection of RBV as the theoretical basis for viewing the company's stance on corporate sustainability does not stem from the "comfort" of obtaining win-wins from efficiency gains and their impact on competitiveness. Rather, it stems from a call for companies to develop resources and organisational competences autonomously and fulfil the sustainable development goals. However, given that the global sustainability challenge demands the collaboration of multiple stakeholders, this view also has its limitations. Thus, RBV is not the one and only view of the firm adopted for this research; it represents a somewhat autonomous starting point for manufacturing companies. Given the goal of this research, the choice of RBV is open to confutation.

Standards for sustainability management

The aim of this research is to develop an assessment framework for sustainable manufacturing to make corporate management understand how to positively influence relevant economic and environmental sustainability performance.

The interplay between management and assessment can be explained as follows: sustainability assessments are the backbone of management systems, when management systems are data-driven and when key performance indicators (KPIs) - within performance management systems - require methods and tools to be calculated and disseminated within the company.

In categorising indicators for sustainable manufacturing, Joung et al. (2013) rightly pointed out the connection between the three sustainability pillars and compliance/conformity with the management objectives, industry standards, and policies of the organisation.

Almeida et al. (2014) showed that the concept of integrated management systems, caused by a need for synergies and centralising efforts, became relevant after the ISO 14001 standard's (ISO 14001, 2015) publication on environmental management, and with the release of OHSAS 18001 (Occupational Health and Safety Management (OHS) (BS OHSAS 18001)[5]). In the manufacturing sector, other standards suitable for integration on a management-systems level include the energy management standard (ISO 50001, 2018) and the family of ISO 9000 standards (ISO 9000, 2015), which address various aspects of quality management.

From a competitiveness perspective, despite the benefits of adopting integrated management systems (Almeida et al., 2014) (including better external image and improved customer satisfaction), the same group of authors and other scholars (Karapetrovic, 2003, Zutshi and Sohal, 2005, Karapetrovic et al., 2006) also pointed out the challenges of the integration process. The most-reported difficulties by Almeida et al. (2014) are: lack of human resources, lack of individual concerns of the people involved and lack of government support.

Given that assessing social sustainability performance is beyond the scope of this research (see Section 1.6) and based on what has been stated previously, integrated management systems are excluded from further investigation. Indeed, evaluating the contribution to corporate sustainable manufacturing of integrated management systems would require a proper understanding of how BS OHSAS 18001 plays out in production systems, with humans being at the core of the investigation. Furthermore, given that the problem of integration between management systems standards is found at the human-factor and institutional levels (also beyond the investigative scope of this research, due to the choice of RBV), this

[5] ISO 45001 replaced BS OHSAS 18001, from June 2018.

researcher has no way of addressing the issue of problematic management systems integration.

Environmental management systems

The ISO 14000 family of standards for environmental management (ISO 14000) gives comprehensive support for managing the environmental performance of manufacturing companies. It helps facilities create quantifiable goals to reduce their environmental impact and monitors progress through a policy-like approach and procedural instruments, such as systematic auditing and management reviews (Arimura et al., 2016). According to (Yang et al., 2010), adopting environmental management systems provides manufacturing companies with proven support in the enforcement (and related success) of EU directives, such as Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS), as noted by Walther and Spengler (2005).

However, a study of approximately 4,000 manufacturing facilities in seven member countries of the Organisation for Economic Co-Operation and Development (OECD) run by Johnstone and Labonne (2009) showed that, for larger facilities, environmental “signalling” (as opposed to genuine intent to continually improve environmental performance) is a strong motivator for adopting environmental management system certifications.

Arimura et al. (2016) reported that ISO 14001 certification (ISO 14001, 2015) is one of the most widely used, voluntarily adopted environmental management certification system. In December 2014, according to a survey set up by the International Organization for Standardization (ISO) in 2015 and reported by the same authors, 324,48 facilities worldwide had received ISO 14001 certification. A relevant question asked by environmental engineering and sustainability management scholars is whether adopting environmental management systems translates into environmental performance improvement of the companies in question and, if so, to what extent. Arimura et al. (2016) sought an empirical answer to this question. They conducted a study based on data from a survey developed by the OECD Environment Directorate and completed by manufacturing companies. This was the same survey used by Johnstone and Labonne (2009) and involved 14 academic researchers and advisory group members across seven OECD countries. Furthermore, Arimura et al. (2016) summarised the findings of the available scientific literature dealing with empirical studies on the matter.

The authors concluded that empirical evidence of the effectiveness of ISO14001 on environmental performance was “unclear” and pinpointed two possible reasons for the diversity of results: 1) institutional variations across countries and 2) idiosyncrasies

related to the type of environmental impact being assessed. This means that there are differences in how institutions put less/more pressure on the disclosure of environmental impact of manufacturing businesses and on the methodology with which the environmental impact assessment is carried out.
As this research work focuses on leveraging the value of sustainability assessment methods/tools for effective use by management and management systems, part of the research efforts of this work will be dedicated to the use of life cycle assessment (LCA) methodology (ISO 14040, 2006) for evaluations at production systems level.

Life cycle assessment

LCA belongs to the ISO 14000 family of standards. LCA is a tool that has long been included in environmentally-inclined decision making frameworks, as illustrated by Miettinen and Hamalainen (1997). This research uses environmental life cycle assessment (Rebitzer et al., 2004, ISO 14040, 2006) as a support tool for decisions in the production development phase. In this type of use, LCA used for environmental cost-benefit analyses (Pearce et al., 2006) at production-system level is a possible methodological avenue for fulfilling the aim of this research, especially RQ1.
However, the reader should be aware that the type of LCA analysis actually conducted in this work qualifies as *screening* LCA. This is because an ISO-compliant LCA would have demanded a critical third-party review of all the steps prescribed by ISO 14040 (ISO 14040, 2006). Hence, “life cycle thinking” (Mascle and Zhao, 2008) best describes the approach with which environmental analyses were carried out in this research. The environmental impacts considered in this work stem from the characterisation step of the LCA framework, the Life Cycle Impact Assessment (LCIA). These impacts belong to defined impact categories and are calculated as metrics and indicators (Finnveden et al., 2009). Most of the time, the LCIA indicator being analysed in this work was global warming potential (EPA, Pfleiderer et al., 2018), due to the focus on energy efficiency in this research.

2.2.2. Focus area: sustainability assessment methods and tools in manufacturing

This sub-section illustrates three specific applications of sustainability assessment methods and tools: energy efficiency assessment, technology assessment, organisational maturity assessment. In general, researchers aiming to support manufacturing companies in becoming economically and environmentally sustainable can develop one or more types of solution support, targeting specific aspects of the organisation: technological, managerial, behavioural, institutional, and so on. The answer that a specific scientific community in sustainable manufacturing provides when supporting corporate sustainability is a methodological one, falling under a vast umbrella of sustainability assessment tools (Pope et al., 2004, Sala et al., 2015, Pope et al., 2017). Sala et al. (2015) describe a sustainability assessment tool as "a complex appraisal method. It is conducted for supporting decision-making and policy in a broad environmental, economic and social context, and transcends a purely technical/scientific evaluation".

Ness et al. (2007) developed a taxonomy of sustainability assessment tools used in industrial sectors, which was further enriched by Taisch et al. (2013). The latter divided the tools into four categories: sector-and-country-related assessments (such as input-output energy analysis), indicators/indices (including a human development index), product-related assessments (like LCA) and project related assessments (such as full life cycle cost accounting). According to the goals of the assessment, these tools can be used to evaluate a production system's development choices (such as layout planning) and also choices on an operations management level (such as energy management practices). Among many other sustainability assessment tools already available to industry and belonging to LCE are life cycle assessment (LCA) (ISO 14040, 2006, ISO 14044, 2006) and material flow analysis (Smith and Ball, 2012, Brunner and Rechberger, 2016).

Assessing energy efficiency

This researcher's first "contact point" with management's needs (in terms of sustainable manufacturing) was in early 2014 and dealt with energy management in manufacturing as a lever to increase industrial energy efficiency performance. The concept of energy management in the scientific literature was extensively reviewed by May et al. (2017).

Back in 2011, the Energy Management Standard 50001 was issued. In 2018, this was replaced by a new version (ISO 50001, 2018) According to the description of the standard, "energy performance indicators (EnPIs) and energy baselines (EnBs) are two interrelated elements …to enable organisations to demonstrate energy performance improvement". In the standard, the energy management system "is based on the Plan-Do-Check-Act (PDCA) continual improvement framework and incorporates energy management into existing organisational practices" (ISO 50001, 2018).

At around the same time as ISO 50001 was issued (in 2011), scholars in the field of energy efficiency in manufacturing were exploring opportunities to monitor energy consumption patterns and thereby improve the environmental performance of manufacturing systems (Vijayaraghavan and Dornfeld, 2010). Dahmus and Gutowski (2004) had already investigated energy consumption patterns at a machine-tool level and had presented their case for reducing a machine's total energy consumption by reducing its idling time. As a matter of fact, the authors noticed that "the specific cutting energy accounts for less than 15% of the total energy consumed by a modern automatic machine tool during machining". A year later, Gutowski et al. (2005) reconfirmed the validity of the case for reducing "idling times" based on energy measurements for machining operations carried out at Toyota. In that study, Gutowski et al. (2005) noted that over half of the energy used by the machine tool came from the pumping of coolants, lubricants and hydraulic fluids, which are then treated as waste products.

From this background, the scientific community of researchers in sustainable manufacturing started answering Vijayaraghavan and Dornfeld (2010) to correlate energy usage patterns with the specific operations being carried out in manufacturing systems. The work of these scholars did not overlap with or substitute the standardisation efforts. Given the opportunity to use more granular information at machine level, they instead aimed to encourage adoption of the standard. ISO 500001 does not prescribe any specific performance criteria (Kanneganti et al., 2017).

Assessing technology

New digital technology is and will continue to be embedded in existing production systems. Each case has a question as to what the environmental impact of this technology might be in the "hosting" production systems and product life cycles.

Technology assessment was first formally mentioned in 1995 by a dedicated office in the United States (Congress, 1995). While re-elaborating upon key methodological studies in the field of technology assessment, Fleischer and Grunwald (2008) stated that technology assessment aims to provide knowledge and orientation for action and decision-making on technology and its implementation in society. This research applies technology assessment to emerging technologies for production systems, in which technology assessment can be seen as interdependent with environmental impact assessment (Glasson and Therivel, 2013) and specifically LCA. The synergy between technology assessment, environmental impact assessment and LCA has been elaborated upon by Loveridge (1996), as reported by Tran and Daim (2008).

Assessing organisational maturity

A key concept within corporate strategic alignment (which RQ2 tackles) is "organisational capability", sometimes called "capacity" or "competence". The McKinsey management consultancy defines capability as "anything an organisation does well that drives meaningful business results" (McKinsey, 2010). It follows that a consistently performed activity which needs to use the resources and knowledge of the organisation becomes a capability only if it directly contributes to the achievement of that organisation's goals. Differences in the notion of organisational capability depend on the industry in which they are acquired. In this research, organisational goals are restricted to corporate sustainability goals, which cascade to manufacturing and other relevant business operations.

Examples of core manufacturing capabilities in the context of sustainability performance improvement were given by Goldstein and Hilliard (2009) and Amini and Bienstock (2014). In the latter, pollution prevention and product stewardships are examples of core capabilities derived from a natural resource-based view of the firm. A car manufacturer which also competes on the basis of environmental responsibility would strive to acquire the capability of remanufacturing components and building a closed-loop supply chain. The more this capability is “absorbed” into the operations of factories and supply chains (such as green procurement being aided by a shared ICT platform in the supply chain), the more “mature” the organisation is in handling that capability and thus achieves its strategic goals through sustainable operations.

Capability management is one of the possible modelling avenues to take in fulfilling RQ2. Indeed, capability management stems from a deliberately chosen theoretical view of an organisation; the RBV, as previously explained. Capability management is operationalised by assessment, using rating-like tools, normally called “capability maturity models”. The idea behind a maturity model is that if a company receives a score of two out of a maximum of five, it would be encouraged to build a roadmap for acquiring resources and adopting practices, ultimately reaching level five. The forefather of those models came from the computer sciences and was applied to software development (Paulk et al., 1993). Wendler (2012) reviewed 237 publications on maturity models in 20 domains, albeit not restricted to production engineering and corporate sustainability. A promising and relevant model from which this research began (and aimed to further develop) was the sustainable manufacturing maturity model from Mani et al. (2010) at the National Institute of Standards and Technology (NIST). This model focuses on aspects of manufacturing process performance’s stability (van Schalkwyk, 1998) and combine those with the use of tools in the realm of life cycle management (Westkämper et al., 2001) .

2.3. State of the art research in the focus area

This section presents the state-of-the-art research that defines the boundaries of the relevant body of knowledge.

It is necessary to point out that the account on sustainability assessment tools, energy efficiency, technology assessment, capability assessment did not come from a systematic literature review that this researcher may have undertaken. In fact, none of the appended papers (*Paper I, II…XII*) published what it is ascribable to a systematic literature review (Bell et al., 2018). However, the method with which secondary data from the academic literature was collected and scrutinised is explained on page 52, in Section 3.2.3 Data analysis.

This section starts with an account of the sustainability assessment tools (either stand-alone or embedded in framework) already developed by academics, and then explores the difficulties of the research-to-practice transfer of those tools and frameworks. It then continues with analysis of specific research gaps found in the body of knowledge of all the topics that were introduced in the previous chapter. Each heading is now accompanied by the research question that the topic addresses.

2.3.1. Sustainability assessment methods and tools (RQ1 and RQ2) in manufacturing

The list of relevant work that is about to be included considers process-oriented assessment published from 2011. Furthermore, these pieces of research were selected on the criteria that at minimum they encompassed both economic performance and environmental performance. Social sustainability may or may not have been considered in addition to the other two "pillars" of sustainability.

Literature reviews of corporate sustainability assessment tools, which focused on but were not limited to the factory/production system level in manufacturing companies, were carried out in seven studies hereby summarised:

- Gunasekaran and Spalanzani (2012): a review on "tools, techniques, and some performance measures and metrics" for sustainable business development in manufacturing and services.
- Rosen and Kishawy (2012): a review of sustainability assessment "tools like design for environment, life cycle assessment and other environmentally sound practices" (Rosen and Kishawy, 2012) that facilitate the integration of sustainability criteria in industrial designers' activities. Different abstraction levels could have been adopted when encompassing approaches and practices underneath the "tool" umbrella.
- Chen et al. (2013): a set of twelve sustainability assessment tools between 1997 and 2010 were evaluated by using four criteria that assess the fit of the tool for factory sustainability assessment. A perfectly "fit" assessment tool could not be identified.
- Lee and Lee (2014): a proposed taxonomy for bibliometric/bibliographic applications to structure the multi-faceted body of research in sustainability assessment in manufacturing in scientific databases.
- Moldavska and Welo (2016): a literature review of the field of sustainability assessment in manufacturing. Then, the authors make the case for the applicability of

a system-thinking approach to the development of a sustainability assessment tool for manufacturing companies. Instantiations of what a “system-thinking approach” means in practice are provided.

- Ahmad and Wong (2018): a review of 144 indicators for sustainable manufacturing. Account on the evolutional progress and maturity of sustainability indicators, coupled with advice for indicator developers.
- Madanchi et al. (2019): a review on sustainability assessment tools in manufacturing confirmed that sustainability assessment is becoming a “rapidly developing area with a growing number of frameworks and tools with a wide range of different focus levels”. Given the scope of analysis of the extant tools and issues of applicability in manufacturing companies, Madanchi et al. (2019) confirmed gaps (in particular **gap 1**, already presented, and **gap 6**, on page 27) which this researcher found from her own review of the literature.

Several practice-oriented academic researchers have developed one or more sustainability assessment tools and, often but not always, organised these tools into frameworks and architectures of information for performance improvement purposes. This is made possible thanks to the integration of empirical data from manufacturing companies or from hypothetical examples. The difference between the list of publications below and the list above is that the former contains pieces of work that come from research and development activities dedicated to the development of frameworks targeting industrial applications rather than to the critical review of the extant research. Naturally, framework developer academics carried out literature reviews to different extents. Relevant pieces of work that explicitly put forward assessment frameworks (as opposed to individual models and tools) for sustainable-manufacturing performance management are published in the following 14 publications:

- Pham and Thomas (2011): a conceptual framework limited to “traditional” operational performance reinforced by concepts of lean manufacturing and agile management. The framework links to strategic aspects.
- Gunasekaran and Spalanzani (2012): a framework for sustainable business development in manufacturing and services, whose building blocks are extrapolated from an extensive literature review. Examples of the building blocks of the framework are “sustainability in production operations” and “sustainability through reverse logistics”.
- Chen et al. (2014): a software-based, rapid, holistic, continuous-improvement tool for sustainable manufacturing which leverages visualisation capabilities (spider chart, Pareto curves) to support continuous improvement and management’s decision making.

- Zampou et al. (2014): a prototype of a framework for "energy-aware information systems in manufacturing" (Zampou et al., 2014) providing two functionalities: energy monitoring and energy-aware analytics.
- Dubey et al. (2015): a "world-class sustainable manufacturing (WCSM) framework" focused on the triple bottom line of sustainability. The framework originated from a literature review and was converted into a measurement instrument whose psychometric properties were tested with several statistical analyses.
- Garbie (2015): an analytical, software-based framework calculating an integrated sustainability index and the influence of each sustainability "pillar" within the triple bottom line. The case study is "hypothetical" (Garbie, 2015).
- Tan et al. (2015): a sustainability indicator framework for manufacturing SMEs generated through a systematic indicator selection method. The framework bring concepts and definitions related to sustainable manufacturing. User companies are Singaporean SMEs.
- Zhang and Haapala (2015): an assessment framework measures triple-bottom-line indicators per production scenario which integrates pairwise comparison and outranking methods (e.g., AHP) to assist decision making.
- Moldavska and Welo (2015): an indicator-based framework for sustainable manufacturing which is based on value-chain activities (e.g., marketing, product development, HR management) presupposing a customer-oriented view. The framework arose from an extensive literature review.
- Rödger et al. (2016): the "Sustainability Cone" is a conceptual, holistic framework that integrates life cycle thinking into product and production development activities. The "cone" has different functionalities as horizontal layers: at its top, the functional unit (for LCA), and at the bottom, the tool. The framework was applied in the car development process.
- Moldavska and Welo (2016): the assessment framework results from a combination of tools like analysis of multiple viewpoints, "conceptagon", and model-based systems engineering. The framework was development according to best practices learned from the practice-oriented literature being reviewed.
- Bilge et al. (2017): framework that maps sustainability value-creation factors per product-life cycle stage and corporate oriented life cycle stages (e.g., innovation, education, and management, among others). It encompasses a challenging holistic view to convert into measurement.
- Jiang et al. (2018): three-dimensional (economic, environmental, and social) sustainability assessment model to analyse the corporate sustainable performance based on principal component analysis. What the authors called "a framework", this researcher would have called "tool" or "methodology" instead.

- Madanchi et al. (2019): a framework based on existing integrated sustainability assessment tools. The framework calculates a composite sustainability index attached to a manufacturing company. The authors believe that the approach is innovative and promising as the run time of the framework is 30 minutes and facilitates sustainable decision making internally and sustainable investing externally ("internal" and "external" refer here to the perimeter of the manufacturing company).

The assessment frameworks reported in the list above constitute a further development, in most cases, of existing works being reviewed by the developers of the framework themselves. Then, in any given study, the framework is being demonstrated in a case study. In the scientific literature, there are individual tools which are relevant for this research, and are not encompassed or categorised by their authors as a framework. Relevant tools are worth mentioning in this document. However, they will be a few, only starting from 2014. Such a narrowed choice is a consequence of the major size of the body of knowledge that is rapidly expanding (Madanchi et al., 2019). Furthermore, a new list of a series of individual sustainability assessment tools might be redundant, given that the works that are listed above already contain several sustainability assessment tools within which are individual tools. Relevant sustainability assessment tools for sustainable manufacturing published in the scientific literature from 2014 are:

- Li et al. (2016): a "sustainability cockpit": a discrete event simulation (DES) factory model for continuous assessment targeting SMEs. The cockpit allows 'what-if' analyses and optimisation of operational and environmental performance.
- Singh et al. (2016): a fuzzy rule-based expert system that elicits the measurement of sustainability performance based on triple bottom-line framework thanks to 16 metrics reviewed from the literature.
- Faulkner and Badurdeen (2014): a sustainable value stream mapping ("Sus-VSM) based on reviewed metrics to measure the triple bottom line of sustainability in the manufacturing sector.
- Jonkutė and Staniškis (2016): "SURESCOM" (Sustainable and Responsible Company) is a multi-faceted model for business development purposes for sustainable production and consumption that comes with an algorithm for the model application and a composite index for sustainability evaluation.

An exception to the criterion with which the list above was generated is the inclusion of the OECD sustainability toolkit (Bordt, 2009) as a set of tools needing mention. The toolkit was in fact published in 2009 and by a non-academic organisation. However, The toolkit offers "seven steps to environmental excellence", speaks to manufacturing SMEs primarily, and invites manufacturing companies' management to measure and control eco-efficiency and resource-reuse aspects, among other sustainability management practices.

Given the plethora of sustainability assessment tools from academia, a practical problem raised by academics themselves was a lack of guidelines and criteria on how to choose between these tools (Gasparatos and Scolobig, 2012) (**gap 4**).

There is also a timing issue regarding the application of sustainability assessment tools. Peruzzini and Pellicciari (2016) favour using methods for designing sustainability and LCA from the conceptual stage of industrial manufacturing systems' design. Here, there is typically low data availability but a high chance of influencing the outcome of the product and production development process (Kaebernick et al., 2003) (**gap 5**). Indeed, "environmental excellence begins during initial design phases", claims Winkler (2011), stating that "during the stages of product conception and design, most of the environmental, social and economic cost factors are already determined, sometimes up to 80%". In this research, the terms "concept"/ "conceptual", applied to a production system, indicate one that does not yet exist (the same applies to products) but which results from the possibility of an impactful change to an existing production system (by, say, the introduction of a novel piece of technology).

Existing assessment tools in academia are valuable for the specific purposes of analysis, but seem unable to serve as stand-alone support for the manufacturing industry as it transitions to sustainability. Stakeholders need to be involved in sustainability assessments for decision-making purposes (Nee et al., 2013, Moldavska and Welo, 2016). Furthermore, many assessment tools stem from a reductionist approach (Moldavska and Welo, 2016, Peruzzini and Pellicciari, 2016) unsuited to the systemic nature of sustainability. On the other end of the spectrum, some other sustainability assessment tools may be integrative and open in their design so much so that the sustainability assessment "fits poorly with the entrenched structures, cultures and motivations of conventional authorities" (Dijk et al., 2017). Hence, both reductionism and holism seem to represent a problem from the perspective of the industrial application of sustainability assessment tools (**gap 6**).

The scholars who have been cited in this section corroborate the gaps that were previously identified (gap 1 and gap 2) which motivated the generation of RQ1.

Arguably, the reason behind researchers wanting to develop new tools or "upcycle" tools is to overcome some of the gaps that have been previously spotted.

Outlook on sustainable manufacturing/production KPIs (RQ1 and RQ2)

KPIs for economically and environmentally sustainable manufacturing at machine level and factory/production system level are within the scope of this research, particularly energy efficiency KPIs. Indeed, energy efficiency is one of the best-known performance areas in manufacturing; if the economic and environmental sustainability pillars are viewed only from within the system boundaries of the company, it is visibly able to merge them.

At the factory level, KPIs for sustainable manufacturing of interest to this research have been reviewed by Veleva and Ellenbecker (2001), Joung et al. (2013), Winroth et al. (2016) and Kianian et al. (2018). Reviews of energy efficiency KPIs at a factory level come from Karnouskos et al. (2009), Bunse et al. (2011) and May et al. (2013).

Feng and Joung (2009), Rosen and Kishawy (2012), Joung et al. (2013), Winroth et al. (2016) seemed to agree on the proliferation of KPIs for sustainability performance management on a factory/production system level. Hence, one of the challenges for management is coming up with a systematic process to select relevant KPIs, given the needs of the assessment or performance management (Kianian et al., 2018) (**gap 7**). On the other hand, Löfgren et al. (2011) noted that although "establishing performance indicators using LCA has already been proposed (Hermann et al., 2007, Zobel et al., 2002) and applied (Perotto et al., 2008) […] these authors use the more conventional cradle-to-grave system boundaries, including all material inputs to the manufacturing site". This contrasts with the product-life cycle view embedded by the definition of sustainable manufacturing and suggests a need for indicators encompassing such a view (**gap 8**). Eminent scholars have recognised this gap in the field of LCE applied in manufacturing research (Hauschild et al., 2017).

2.3.2. Assessing energy efficiency with modelling and simulation approaches (RQ1)

This research began with an interest in the use of discrete event simulation (DES) (Zeigler et al., 2000) for operational and environmental performance analyses in production systems' machining operations. The value of synchronising life cycle thinking with the capabilities of simulation tools was what generated the application area of life cycle simulation, "a method to evaluate the performances of life cycles (such as life cycle costs and environmental impacts) for design and planning of life cycles based on discrete event simulation" (Umeda et al., 2012). However, life cycle simulation appears better suited to business decisions and design-for-environment decisions on product-service systems (Garetti et al., 2012) than production systems as such. Thiede et al. (2013) offered a comprehensive overview of the use of system modelling and simulation approaches for considering the environmental aspects of manufacturing. Examples of practical work of this kind in production/manufacturing systems come from a considerable number of scholars whose studies (Heilala et al., 2008, Herrmann et al., 2011, Despeisse et al., 2013, Johansson et al., 2009, Lee et al., 2014, Cerdas et al., 2017, Li et al., 2017) were considered relevant for this research. Recent simulation-based work on energy efficiency in machining comes from Teiwes et al. (2018), Dehning et al. (2019), and by Blume et al. (2017) (in the metal mechanic sector only).

Several scholars, such as Rohdin (2006), Rahimifard et al. (2010), Bunse et al. (2011) and May et al. (2017), have thoroughly reviewed barriers to and opportunities for effective energy management and energy efficiency in manufacturing, mostly with respect to the energy consumption of machine tools. In particular, Rahimifard et al. (2010) presented a decision support tool based on an energy simulation model of a production system. The authors claimed that such an approach “could further support detailed LCA studies, providing a greater insight into the energy consumption during the manufacturing phase of a product life cycle”.

Bunse, Vodicka et al. (2011) showed the results of a gap analysis between state-of-the-art and industry needs in the area of energy management in production. Here, the authors called for energy efficiency KPIs suited to process and plant level and for standardisation (**gap 9**). Two years later, Taisch, Sadr et al. (2013) encouraged the introduction of energy efficiency as a key enabler of sustainability assessments.

2.3.3. Assessing technology with a life-cycle thinking approach (RQ1)

A question which several fellow manufacturing/production researchers are investigating is how Industry 4.0 presents challenges and opportunities for sustainable manufacturing and to what extent (Stock and Seliger, 2016, Kamble et al., 2018) (**gap 10**). More specifically, some researchers also address specific impact areas of Industry 4.0 with respect to sustainability, such as process safety and environmental protection (Gobbo et al., 2018, Moktadir et al., 2018) and broader environmental issues (de Sousa Jabbour et al., 2018). Thiede (2018) demonstrated two examples of environmental breakeven analyses in two instantiations of cyber physical production systems. Other studies reflected on what the development of cyber-physical systems would mean for remanufacturing, such as (Yeo et al., 2017). Product end-of-life strategies were assessed by Barkmeyer et al. (2017) via environmental breakeven analyses as well.

Technology assessment (TA) using LCA could provide a way to answer questions about the environmental impact of novel, emerging production technologies.

However, Gutowski (2018) pinpointed several problems of misrepresentation in how an R&D technology is being modelled in LCA analyses, advocating a human-behaviour based LCA.

Some scholars discussed the limitation of using LCA in corporate environments in several studies (Ny et al., 2006, De Benedetto and Klemeš, 2009, Rex and Baumann, 2008, Baumann et al., 2011) and Cerdas et al. (2017) discussed the above problem in manufacturing specifically. This roadblock should be considered when applying LCA for TA purposes in manufacturing companies (**gap 11**).

2.3.4. Assessing organisational maturity with a capability-based approach (RQ2)

From the end of the first decade of the 2000s and starting with Teece (2007), the "foundations" of capabilities for sustainable competitive advantage in manufacturing (such as selecting new technologies and knowledge management) began appearing in the academic literature. In (Teece, 2007) and (Teece, 2018), sustainability is represented as a "dynamic capability" (Eisenhardt and Martin, 2000) and also presumably as a stratagem to remedy the short-sightedness of the inward-looking, resource-based view of the firm.

Although there is a proliferation of organisational maturity models (assessments) in the literature (Wendler, 2012, Reis et al., 2017), models evaluating the maturity of capabilities for sustainable manufacturing are scarce in the literature (not to be confused with models dedicated to fostering *sustained competitive advantage*).
Exceptions come from: Pigosso et al. (2013) (in eco-design practices), Gonçalves Machado et al. (2017) (in sustainable operations management) and Mani et al. (2010), with a conceptual model integrating life cycle management into the "familiar" structure of the Capability Maturity Model Integration (CMMI Institute, 2019). Furthermore, in his meta-review of 237 articles, Wendler (2012) exposed a clear research gap in evaluating and validating developed maturity models (**gap 12**). Starting with the model by Mani, Lyons, and Sriram (2010), revisiting it with empirical data and validating it in industrial practice is one way of contributing to the field of capability maturity in sustainable manufacturing. Furthermore, a validated capability maturity model of this kind also allows **gap 3** to be addressed. This brought about RQ2.

2.3.5. Overview of research gaps

Table 1, on the next page, summarises all the research gaps that were detected.

Table 1: Research gaps.

Gap #	Gap	Item within theoretical framework, HOW vs WHAT to measure	Main references	RQ#
1	Accessibility of sustainability assessment tools and methods for industry. Tools for sustainability assessment from applied research may not be easily accessible to industry. Alternatively, if tools are available, manufacturing companies might not own the necessary competences to conduct sustainability assessments.	Sustainability assessment tools How to measure	Paju et al. (2010), Raoufi et al. (2017)	1&2
2	Call for a focus on processes and production systems (as opposed to product design only), if all the three pillars of sustainability must be addressed in manufacturing.	Sustainability assessment tools What to measure	Jayal et al. (2010), Rödger et al. (2016), Ahmad and Wong (2018)	1&2
3	Support for formulating and developing sustainability strategy.	Capability assessment How to measure	Satyro et al. (2017), McKinsey & Co (2017)	2
4	Overabundance of sustainability assessment tools and lack of guidelines and criteria on how to choose between these tools.	Sustainability assessment tools How to measure	Gasparatos and Scolobig (2012)	1&2
5	Use of methods to design for sustainability and LCA from the conceptual stage of industrial manufacturing systems' design. Issue with this choice is the scarcity of data, which means postponing any serious influence in terms of performance.	Sustainability assessment tools What to measure	Kaebernick, Kara, and Sun (2003), Rosen and Kishawy (2012), Peruzzini and Pellicciari (2016)	1
6	Many assessment tools stem from a reductionist approach not suited to the systemic nature of sustainability.	Sustainability assessment tools How to measure What to measure	Moldavska and Welo (2016), Peruzzini and Pellicciari	1&2

Gap #	Gap	Item within theoretical framework, HOW vs WHAT to measure	Main references	RQ#
			(2016), Dijk et al. (2017)	
7	Proliferation of KPIs for sustainability performance management.	Economic and environmental sustainability performance management in production systems. What to measure	Feng and Joung (2009), Rosen and Kishawy (2012), Joung et al. (2013), Winroth, Almström, and Andersson (2016), Kianian, Daly, and Andersson (2018)	1&2
8	Indicators of sustainable manufacturing proposed by some scholars, even when using LCA, contrast with the product-life-cycle view embedded by the definition of sustainable manufacturing.	Environmental sustainability performance management How to measure	Löfgren, Tillman, and Rinde (2011)	1&2
9	Call for energy efficiency KPIs suitable for process and plant level and for standardisation efforts.	Environmental sustainability performance management What to measure	Bunse, Vodicka et al. (2011), Taisch et al. (2013)	1
10	Finding out the extent to which Industry 4.0 presents challenges and opportunities for sustainable manufacturing.	Sustainability assessment tools How to measure	Stock and Seliger (2016), Kamble, Gunasekaran, and Gawankar (2018)	1&2
11	Limitations of usability of LCA in corporate environments. Possible issue	Life cycle assessment Technology assessment	Ny et al. (2006), Rex and Baumann	1

Gap #	Gap	Item within theoretical framework, HOW vs WHAT to measure	Main references	RQ#
	for technology assessment when conducted in manufacturing companies	How to measure	(2008), De Benedetto and Klemeš (2009), Baumann et al. (2011), Cerdas et al. (2017)	
12	Evaluating and validating developed maturity models.	Capability management How to measure	Wendler (2012)	2

An overview of the key words of the literature that have been reviewed and the logical connection between them is offered through the concept map in Appendix A on page 133. Figure 8 summarises the contents of this section. The section culminates in the identification of two research priorities. Priority 1 identified an avenue for a solution to RQ1 and Priority 2 an avenue for a solution to RQ2.

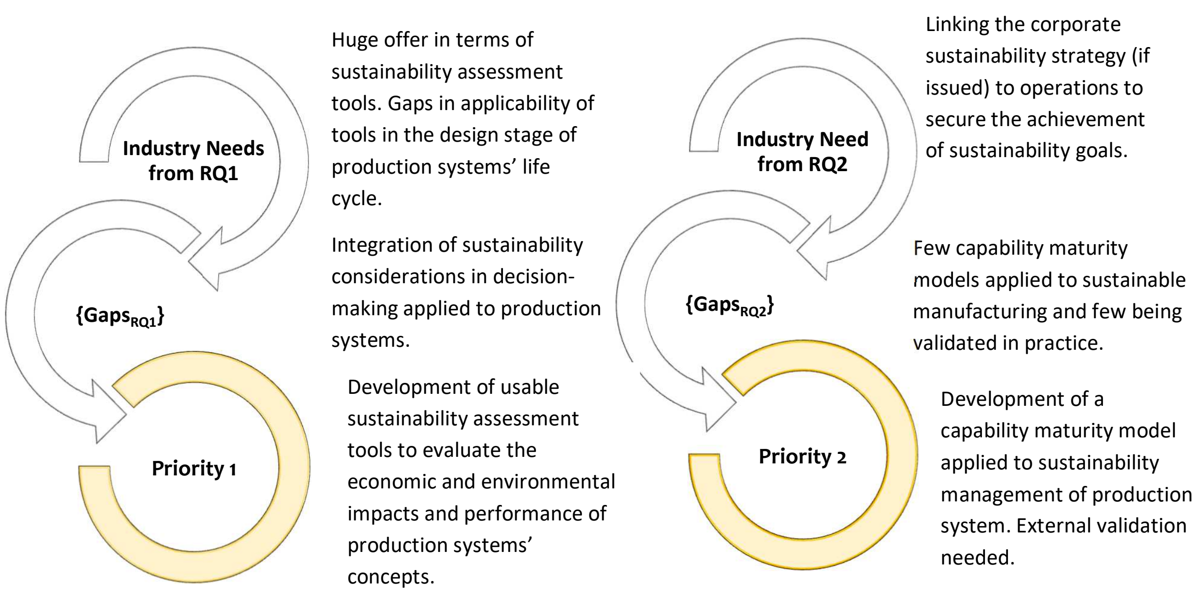

Figure 2: Identification of research priorities.

3. Research design and methodology

A discovery is said to be an accident meeting a prepared mind.

Albert Szent-Györgyi, (1893 – 1986)
Biochemist and Nobel laureate in medicine

3.1. Research design

A research design "represents the structure that guides the execution of a research method and the analysis of subsequent data" (Bryman and Bell, 2011). This chapter illustrates how the research has been designed and conducted since its inception in 2014 and, in these illustrations, combines elements of reflexivity. Mills et al. (2010) stated that "reflexivity is operationalized when researchers can articulate their awareness of the interconnectivity between and among themselves, the participants, the data, and the methods they use to interpret and represent their findings". Furthermore, the authors added that reflective "researchers make regular efforts to consider their own thoughts and actions in light of different contexts" (Mills et al., 2010). Reflexivity was also what allowed the epistemological evolution of this researcher to take place, as illustrated in Section 2.1. This chapter concludes with a list of research quality criteria, which will be re-proposed in the Discussion chapter when the assessment framework is evaluated.

Figure 9 (next page) parallels the research process (upper part of the figure) and research design (lower part). The research process part of Figure 9 does not illustrate the duration of the key activities for each step of the process as Figure 2 (page 6) has already done so.

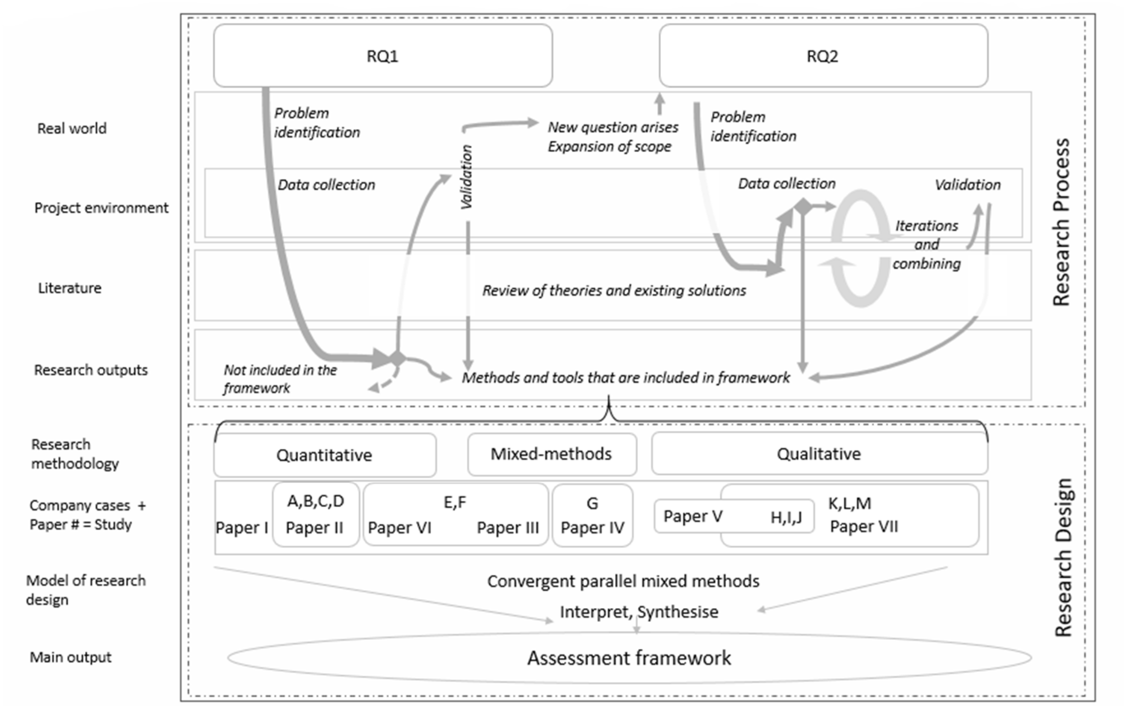

Figure 9: Research process and research design.

The exploration of Figure 9 starts at the bottom. The "main output" is the assessment framework for managing corporate sustainable manufacturing. In this chapter, the assessment framework represents the final object of the theory development process. It should be pointed out that the assessment framework with its methods and tools has not been conceived as a *management theory* (along the lines of Taylor's scientific management, for instance) applicable to corporate sustainable manufacturing. Rather, it was conceived as a proposed "frame of mind" by which management can implement existing and novel methods and tools addressing the identified RQs. From an academic point of view, the assessment framework is a *conceptual framework* which is then exemplified with methods and tools embedded by its structure. Furthermore, the conceptual framework might as well be a convenient "collector" of other methods and tools from the rich body of knowledge from which it originated. That said, since this chapter is dedicated to the research design, the assessment framework will be temporarily referred to as a "theory" in the following paragraphs. Corley and Gioia (2011) acknowledge that there is little agreement on a universal definition of "theory". When arguing on what constitutes a theoretical contribution, the two authors issued a simple definition of theory as "a statement of concepts and their interrelationships that shows how and/or why a phenomenon occurs" (Corley and Gioia, 2011). The very aim of this research indicates that that this researcher has unequivocally decided to bridge existing research gaps in the area of corporate sustainable manufacturing by "wearing the hat" of a method developer. To conduct this type of research, this researcher turned to inductive theory-building from case-study research.

First, a "case" represents a bounded situation or system and can exist on different levels of analysis: a single organisation, a single location, a person or a single event (Bryman and Bell, 2011). Given the focus of this research on corporate sustainability, the cases of interest of this research are company ones.

Eisenhardt described the process of building theories from case study research as a research *design* strategy (Eisenhardt, 1989, Eisenhardt and Graebner, 2007), whereas Yin (2013) defines the case study as a research *method.*

In particular, Yin (2013) defines the case study research method as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident and in which multiple sources of evidence are used". The case study as a research method aims to derive a close, in-depth understanding of one or a small number of cases, set in their real-world contexts (Bromley, 1986).

From a theory-building perspective, this research followed Yin's blueprint of research conduct by filling a "gaps-and-holes template", as expressed by Ridder (2017), where existing theories are the starting point of case study research, and "propositions or frameworks provide direction, reflect the theoretical perspective, and guide the search for relevant evidence". The body of knowledge from which this research started was already rich in theories and solutions and intricate in nature; so much so, that any theoretical contribution added by this research could only have entailed the successful bridging of gaps and holes in this prolific body of knowledge. The extent of the "success" of a contribution is determined not only by whether this research proves trustworthy in its conclusions, but by the judicious identification of relevant *gaps and holes* in the first place.

From an empirical perspective, this researcher used the project environment (see Figure 9) to retrieve data from company cases for theory-building and, to a limited extent, for theory-testing purposes. Company cases included the phenomenon of current interest (need to assess and manage sustainability) and projected it onto "tomorrow's real world". In some cases, a proxy of tomorrow's real world was the development of novel technology demonstrators for factories or facilities in manufacturing supply chains.

Figure 5 (theoretical framework) shows that the topics investigated theoretically and (most prominently) practically were *energy efficiency assessment*, *technology assessment* and *organisational maturity assessment*. These topics are wholly or partially in the realm of the sustainability assessment tools. Solutions within *energy efficiency assessment* and *technology assessment* were deemed suitable to investigate, in order to address RQ1. *Organisational maturity assessment* was deemed suitable to investigate in order to address RQ2. Research into *energy efficiency assessment* started from a personal interest of this researcher, who was able to explore it thoroughly in her Master of Science thesis at Politecnico di Milano, Italy and later at Chalmers. This case was different to the one that triggered the interest in *technology assessment*, as it did not come from an *a-priori* decision to include it in the research scope at the outset. The interest in technology assessment grew spontaneously from constant exposure to the notion of digital transformation which production systems will face; this had been observed, at proof-of-concept level, throughout the five years' research. The focus on *organisational maturity,* via capability assessment*,* started soon after the licentiate seminar which this researcher held in September 2016. The interest in capability assessment, from a theoretical (model) perspective, arose from discussions with peers and research fellows at NIST and from a wish to include managerial aspects within the assessment framework. To concretise the capability assessment so that it served RQ2, this researcher asked manufacturing companies for voluntary participation in the first round of data collection activities.

Within the company cases, the system boundaries of the case chosen for this research were defined in Section 1.4 "Research questions": a production system in a manufacturing company for RQ1, and the organisation of a manufacturing company for RQ2. However, of all the elements within the organisations that were analysed, the production system remains the object of analysis, even in RQ2.

Figure 9 shows that there were 13 case studies resulting in a peer-reviewed research output (company cases A to M). The logic behind the selection of company cases relevant to answering the RQs is illustrated in Section 3.2.1 (purposeful sampling of cases). The same section describes each company case.

Four research studies saw either the participation, or, more ideally, the engagement of one or more companies. In Figure 9, the four research studies are represented by rectangles which group company cases and papers. This researcher was the chief designer and implementer of all the research studies with one exception, the study in case G, where her sole role was supervising the research activities. *Paper I* is another exception. There was no company involvement as it reports on a study which validates the output of *Paper II*. The output of *Paper II* was validated in *Paper I* in a simulation environment. It is evident in Figure 9 that papers belonging to the same study are those linked by the same company cases and contributing to the same RQ. Figure 9 also shows that there was no study encompassing both RQ1 and RQ2. This suggests the presence of two distinct phases of the research.

To put it tautologously, the theory was consolidated once theoretical saturation had been reached (Eisenhardt, 1989). Theoretical saturation was reached once research outputs deemed suitable for inclusion in the framework went through a validity test or when, in theory-building steps, incremental learning was minimal for each case study being analysed. When validation was demanded, the selected outputs were validated in two different environments: a project environment in some cases and real-world in others.

The assessment framework reached its final configuration thanks to an interpretative process applied to all the methods and tools being developed and relating to a reflective practice on how the field of contribution would be enriched by the theory. The act of interpretation signifies a process of synthesis from the mere sum of the individual research outputs to generation of an assessment framework. When this researcher defended her licentiate engineering degree in September 20th 2016, answering RQ1 only, the assessment framework developed up to that point was conceptually different from the final one illustrated in this thesis. Section 3.3 illustrates how the activities of interpretation and synthesis were conducted.

Creswell (2009) talks about models of research design from the perspective of using mixed-methods approaches. From this angle, models of research design are "types of inquiry within qualitative, quantitative and mixed-methods approaches that provide specific direction for procedures in a research design" (Creswell, 2009).
The type of research design model used in this research is called "convergent parallel mixed-methods". Creswell (2009) states that this design occurs when "a researcher collects both quantitative and qualitative data, analyses it separately and then compares the results to see if the findings confirms or disconfirm each other". It is important to clarify that the element which must be either confirmed or disconformed is not the qualitative versus quantitative use of the assessment framework in industry when evaluating its potential to instil sustainability performance improvement. What caused the adoption of the convergent parallel mixed-methods design was examining the possibility of fulfilling the aim of the research by using methods and tools developed from different case studies and offering different types of data and different analytical opportunities.

Figure 9 shows that three of the quantitative and mixed-methods studies were used to answer RQ1, whereas a qualitative study was used to answer RQ2. The latter was divided into two parts: one conducted in Australia and one in Europe. Given the formulation of RQ2 itself, the choice of a qualitative study to answer it seemed the obvious thing to do. Quantitative and mixed-methods studies with a majority of quantitative data were used for RQ1 instead. The upper part of Figure 9 illustrates an outline of the research process that was undertaken. Please note that the transparent lines indicate that this researcher "skipped" a certain area (such as literature) when moving from one step to another. There is a noticeable difference between the pattern of the research process on the "RQ1 side" (left-hand side of Figure 9) and that on the "RQ2 side" (right-hand side of Figure 9); linear and inductive for the first, iterative and abductive for the second. Furthermore, the reader may notice that RQ2 came from the acquired knowledge as RQ1 was answered.
Given the sequence RQ1 → RQ2, it can be said that this research also mirrors a *multiphase mixed-methods* design (Creswell, 2009), although less predominately than in the *convergent*

design. In a multiphase mixed-methods design, "researchers conduct several mixed-methods projects, sometimes including mixed-methods convergent or sequential approaches, sometimes including only quantitative and qualitative studies in a longitudinal study with a focus on a common objective". By using the notation from Morse and Niehaus Morse and Niehaus (2009), the multiphase design process is expressed in [(QUANT +qual) + qual] → QUAL. The assessment framework is actually the product of a synthesis of mixed-method studies and qualitative studies and it is, in itself, qualitative in nature.

3.2. Research methodology

This section synthesises how the research activities took place through the application of research methods for data collection and analysis. A general account of the research methods that were employed throughout the research is given at the beginning of the section. A detailed description of the research methods for each paper is reported in the end of Section 3.2.4, in Table 4 (page 55).

3.2.1. Purposeful sampling of cases

According to Stake (2005), the direction of the case study is shaped by interest in the case. Indeed, in studies undertaken for inductive theory development, case sampling must be "purposeful" (Palinkas et al., 2015), or "theoretical" (Eisenhardt, 1989) as opposed to random. Fourteen company cases (A to N in Table 2, page 43) have been studied, to different extents, in this research. Each one was part of a case study, within either a single-case or multiple-case study design.

Company cases played different roles across all of the research. Some were included in what Stake (2005) calls an "intrinsic case study". Cases which do not constitute intrinsic case studies are called "instrumental case studies" by Stake. This distinction affects the sampling strategy. Stake (2005) actually explains that "in an intrinsic case study, the case itself is of interest. The purpose is not theory-building but curiosity in the case itself. In an instrumental case study, the case itself is of secondary interest. It plays a supportive role, as it facilitates the understanding of a research issue". As Table 2 will show, only Study 2, involving company cases E and F, was an intrinsic case study. It was a major driver behind the creation of RQ1. The rest of case studies were instrumental. The criteria for selecting company cases for inclusion in instrumental case studies translate to what might be called a "company profiling". The criteria were:

- for RQ1: evaluation of the adoption of an emerging technology to be installed in production facilities, in conjunction with a concern about long-term sustainability implications (such as climate, material scarcity). Company size did not appear to be a discriminating factor. OR;

- inadequacy of the available information supporting energy management in production systems, given the technological capability (either now or in the immediate future) to track machine tool operations at granular level. This specification refers to the regular operational stage of production systems. Because of the "advanced monitoring" requirement, only large manufacturing enterprises (like car manufacturers) and OEMs of advanced industrial automation solutions would benefit from such investigation;
- for RQ2: anyone in a leadership position in a manufacturing company who "senses" a mismatch between sustainability strategy and operations in production, but does not have the tools and resources to articulate such a mismatch and address it. At the beginning of the empirical investigations for RQ2, it was observed that this situation is likely to occur in medium-sized enterprises. Indeed, if it the company is a large enterprise, there is a risk of mismatches and misalignment, plus a chance that the company may be equipped with sustainability teams or taskforces to address the problem. On the other hand, in a small enterprise, the chances of mismatches are low, given a lower power-and-influence distance between hierarchical levels;
- ultimately, for both RQ1 and RQ2: a genuine commitment to contribute to the 2030 Agenda, which demands that manufacturing companies dedicate time and resources; these resources are deemed to be competences and short-term "real costs", plus opportunity costs.

Purposeful sampling always took the form of a prior step for including a company in what Figure 9 calls "project environment". Details of all the research projects will be included later, in Table 2 on page 43. Some projects suggested the need for a sustainability assessment of R&D technology. In this research, the evaluated emerging technology was such that the analysis of its adoption entailed a certain degree of complexity. In other words, the adoption of the technology would offer a prospect of potential economy-environment trade-offs or potential rebound effects. An example of technologies for production systems which fall under the aforementioned characteristics includes machines for supercritical carbon dioxide (SC-CO_2) fabric dyeing (part (a) in Figure 10 on the next page). This example comes under the umbrella of hardware-based technology for production systems. However, software also offers promising development in the realm of sustainable manufacturing. An example of eligible technologies on the software front is 3D imaging via the digital twin (part (b) in Figure 10) for robust product-production synchronisation (Wärmefjord et al., 2017). Software technologies fit the scope of this research because they incorporate a whole set of information systems (such as sensors and other data acquisition systems) which mean they run in real time.

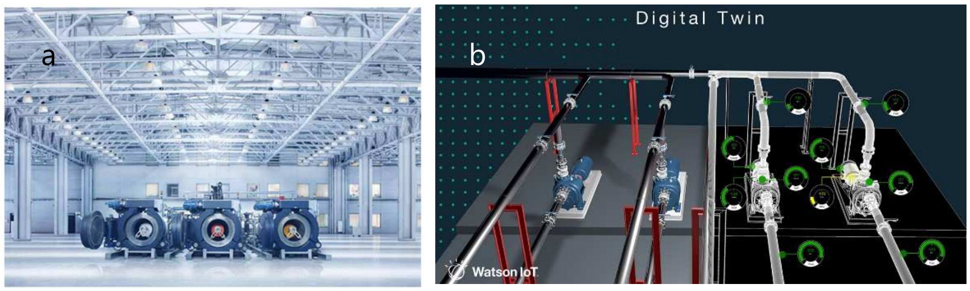

Figure 3: (a) Machines for supercritical carbon dioxide dyeing, water-free, but worth up to 4 M-USD apiece. Source: DyeCoo (2015). (b) Digital twins of intermediate air receivers (tank) in a compressed air system. Source: IBM (2018).

Table 2 on the next page compiles several pieces of information about the case studies in this research. The sequence of the company cases goes from the oldest contact to the most recent.

Table 2: Company cases, RQs, research studies and research projects in which companies were involved.

Company #	Industry (Global Industry Classification Standard) and main product/service	Location	# Employees	RQ #	Study # and purpose of the study	Type of case study	Study in Paper#	Research project and funding agency
A	Machinery. Agricultural and farm machinery	Treviglio, Italy	3,500	1	Study 1 Integration of economic (operational) and environmental factors into management of production operations through the development of novel KPI	Instrumental multiple case study	II	Follow-up study from Master's thesis project under "Production Logistics and Sustainability Cockpit" (PLANTCockpit) FP7-ICT - Specific programme "Cooperation": information and communication technologies (H2020 EU)
B	Industrial conglomerate. Industrial automation	Munich headquarters, Germany	400,000					
C	Semiconductors & Semiconductor equipment Integrated circuits	Leixlip, Ireland	100,000					
D	Machinery Industrial machinery for automotive use	Grugliasco, Italy	14,500					
E	Commercial services & supplies (e-waste pre-processing)	Stockholm, Sweden	20	1	Study 2 Integration of sustainability factors in technology-adoption decisions through development of novel method	Intrinsic single case study	III, VI, VIII, IX	WEEE ID: Kunskap och teknik för mer hållbar återvinning av elektronikskrot Automatic sorting technology for e-waste (VINNOVA)
F	Electronic equipment, Instruments & components (technology developer)	Gothenburg, Sweden	5					
G	Metals and mining. Stone as construction material	Emmaboda, Sweden	80	1	Study 3 Integration of economic (operational) and environmental factors through adoption of standardised data representation of production operations	Instrumental single case study	IV	Effektiv och uthållig naturstensproduktion (VINNOVA)
H	Machinery. Starch moulding equipment	Sydney, Australia	50 (excluding	2	Study 4.1		V, VII	Self-organised six-month study in Australia

Company #	Industry (Global Industry Classification Standard) and main product/service	Location	# Employees	RQ #	Study # and purpose of the study	Type of case study	Study in Paper#	Research project and funding agency
			parent company)		Surveying of organisational capabilities for sustainable manufacturing from company cases. Method development for RQ2 starting from an established yet conceptually mature model of sustainable manufacturing	Instrumental multiple case study		Chalmersska forskningsfonden (scholarship) and the Production Area of Advance at Chalmers. Host: UNSW Sydney through Inbound Research Practicum
I	Machinery. Construction machinery and heavy trucks	Sydney, Australia	500	2				
J	Life sciences tools & services Prescription glasses.	Sydney, Australia	35	2				
K	Transportation infrastructure Ship repair	Landskrona, Sweden	100	2	Study 4.2 Surveying of organisational capabilities for sustainable manufacturing from company cases. Finalisation of method proposed for RQ2 and its conversion to user-friendly interface	Instrumental multiple case study	VII	Ecoprodigi (EU Interreg Baltic Sea Region) – digitalisation for eco-efficiency (Centrum Balticum Foundation, 2019)
L	Transportation infrastructure Ship repair.	Klaipeda, Lithuania	4000 (including the mother company)	2				
M	Marine. Cruise ships.	Turku, Finland	1400	2				
N	Commercial Services & Supplies. End of life services for electronic waste.	Karlskoga, Sweden	25	1	Validation of method developed in Study 2.	Instrumental multiple case study	NA (Published project report)	ReSmaC: Repurposing of Smartphones' Capabilities (Chalmers Research 2018). VINNOVA.

The Data collection section (3.2.2) and Data analysis section (3.2.3) illustrate the research methods and techniques that were employed within the quantitative, qualitative and mixed-methods studies. "Data" in Section 3.2.2 and Section 3.2.3 relates to different types of data: empirical data from the project environments and theoretical data from the scientific literature. A further difference occurs between data collected for theory building activities and data collected for validation purposes.

3.2.2. Data collection

Methods of primary data collection for theory-development purposes

Observations and interviews were the main data collection methods used. In specifying the techniques for the methods, this section gives some examples below but accounts for everything represented in Table 3 on page 49.

Observations

Observations allowed to become familiar with the production facilities and learn about their operations. This was a first or second point of interaction with the project partners (whose characteristics will be explained later in Table 3). The main variables observed were: layout of the facility, sequence of the production flow, capital intensity (such as type and number of machines), consumables used in the facility and labour intensity. Notes were taken during visits to the facilities and photos when possible. Video recording of the most important manufacturing operations only took place in Company J. Observations consisted of factory walkthroughs and shipyard tours. The former happened on eight occasions: Company A and D in Study 1, Company E and N in Study 2, Company G in Study 3, and Company H, I, J in Study 4.1. The latter only took place in Company M, Study 4.2. Observations of the work of technology demonstrators took place twice: Company F in Study 2 and at the site where industrial designers were engaged in a follow-up study to Study 2. Here, the project observed the development of a multi-purpose sensor made from used smartphone components and manufactured via 3D printing. Factory walkthroughs and shipyard visits were hosted by a key person in the research project (one of the study participants) but did not target study participants as observation subjects, typical of "pure" social sciences. Consequently, observations were more of " naturalistic" (Johnson and Turner, 2003) in nature this research.

Structured interviews

For RQ1 only, structured interviews (Bryman and Bell, 2011) were used to obtain quantitative, numerical data about the configuration of the production system. This included material flows, cycle times, buffer sizes, number of operators per line and estimated customer demand volumes. Quantitative data of this kind was used only as input data for discrete simulation modelling, or for environmental analyses at a product-and-production level. Quantitative data was <u>not</u> used for regression or correlation analyses, as future projections depended only on assumptions given in volume-based scenarios. When quantitative data had not been elicited during observations, structured interviews for were held (as with Companies E and F). This data fed into the calculations for Study 2.

This type of data collection was handled "offline", by filling in a template. A Microsoft Excel or Google spreadsheet was shared with the referee person at the company, who was asked to fill in the data. He/she was asked to express their level of confidence and (if uncertain) a measurement range for the data.

In-depth semi-structured interviews

Data for RQ1 referred to operational and managerial aspects of the production systems included in the scope of the research studies and the "connection points" with the upstream and downstream supply chain. For instance, in Study 2 at Companies E and F, part of the data being collected through in-depth interviews covered the current state of Waste Electrical and Electronic Equipment's (WEEE) end-of-life strategy in Sweden. It also examined opportunities to scale up the product's "waste hierarchy", based on the automatic sorter demonstrator developed during the research project.

Data collected for RQ2 scoped both strategic and operational aspects, although the strategic aspects accounted for most of it. A basic example of data collected for Studies 4.1 and 4.2 was the answers to the questions: "what does sustainable manufacturing mean to our company?" and "how do we translate this into our operations?"

Case study research demands a thick description of the cases (Geertz, 1973), not just to collect an abundance of data on a complex problem, but for validity reasons as well (Yin, 2009). In-depth interviews certainly allow collection of enough data to build thick descriptions. See *Papers III* and *IX* for Companies E and F as examples.

17 in-depth, semi-structured interviews (Galletta and Cross, 2013) were carried out in total during the research work, for both RQ1 and RQ2.

Each in-depth interview was carried out only once per study participant, with the exception of two cases, where a participant was interviewed twice during the study; these were in Companies F and J. *Table 3* shows that 10 out of 17 semi-structured interviews were carried out by this researcher, face-to-face with the study participant. Co-authors of some of the appended papers took care of the remaining seven semi-structured interviews. This was the case for the interviews in Companies B, C, D and G.

Interview questions were always shared with the interviewees beforehand, with most questions open-ended. For multiple-case-study designs, an interview protocol (Galletta and Cross, 2013) was used. Appendix B on page 134 exemplifies an interview protocol adopted in *Paper V*, relating to a study addressing RQ2.

Focus groups

The second stage of this research mostly involved focus groups (Bryman and Bell, 2011) led by this researcher. In other words, for the two studies arranged for RQ2, Study 4.1 (based in Australia) and Study 4.2 (based in the European Union).

The choice of focus groups for RQ2 is obvious: RQ2 dealt with the connection between strategic and operational matters when measuring and managing sustainability performance. Thus, it was important to capture views from different organisational roles at the same time. This researcher coordinated four focus groups. The lowest number of participants in a focus group led by this researcher was two and the highest was six. Again, for further details, the reader is invited to refer to Table 3. A core piece of data of interest in RQ2 was the list of core organisational capabilities for sustainable manufacturing per company case, considering the definition of sustainable manufacturing shared by the participants. Participants were a select group of top and middle management at the manufacturing company. Appendix C on page 136 show the list of capabilities for sustainable manufacturing per company case involved, in Studies 4.1 and 4.2.

In some focus groups, it was interesting to note the emergence group thinking, but also the equally relevant situation in which people with different roles disagreed.

Tactics for primary data collection for theory-development purposes

Information from semi-structured interviews and focus-group data was converted into notes or transcriptions. In the case of multiple case studies, data "merged" from the different members of the focus groups or interviews was disseminated to the study participants using a minute-like format (as with Companies K, L and M for example) or with a standard template (Companies H, I and J).

In two pre-studies relating to RQ1 but not translated in peer-reviewed publications, the answer to the question "what is sustainable manufacturing?" was not recorded by transcribing/writing down the interviewee's answer, but by asking them to draw a concept

map (Novak, 1990), which he/she would have discussed with this researcher and those in the focus group.
In retrospect, this researcher believes this to be an effective and efficient method of data collection, when eliciting complex concepts from study participants.

In Studies 4.1 and 4.2 (RQ2) involving the above company cases (Companies H to M), there were five data collection sessions, among 12, where recording of interviews and focus groups was not possible. Those sessions involved 12 of the 18 interviewees for studies across the various company cases under RQ2. In these circumstances, notes were taken by hand by this researcher as the data collection occurred. This was unfortunate, given the need to capture rich data on a complex matter like strategy-operation alignment; something which verbatim data transcripts would have offered. This obstacle compromised the opportunity to undertake any discourse analysis or narrative analysis (Wood and Kroger, 2000) across all the companies involved in RQ2; it would have been a powerful tool to support development of the assessment tool for answering RQ2.

In-depth interviews and focus groups were recorded and transcribed at Companies F, I, L and M. Recording was always possible at Company F, but possible only in one session at company I (the only semi-structured interview conducted). In Companies L and M focus groups were moderated online.
For interviews conducted at Companies B, C, D and G, the main author of the related publications handled the interview and transcription procedure.
If comprehensive notes were taken throughout the interview, a digital copy of the document was created in an online note-taking service. A summary of the interview from those notes was still transcribed into a digital document, such as a standard report template (Study 4.1, which mainly produced *Paper V*) and emailed meeting minutes which resembled the interview protocol sent to the interviewee for checking (Study 4.2, which mainly produced *Paper VII* and derived from *Paper V*).
This is part of something called “member checking” (Birt et al., 2016). Regardless of whether or not the interview could be recorded, the majority of interview data was “winnowed” (Guest et al., 2012); in other words, this researcher focused on the analysis in some of the data but disregarded other parts of it. Naturally, this may present validity issues. Furthermore, the different ways in which this researcher collected and disseminated the interview data makes the number of pages and words of textual information impractical. This weakness may also present validity issues.

Table 3 on the next page lists all the data collection methods adopted for theory-development purposes per company case.

Table 3: Data collection: details per company case.

Company no.	Industry (GICS[6]) and main product	RQ no.	Paper no.	Company role and no. of participants	Data collection method and purpose	Conducted by this researcher?
A	Machinery (agricultural and farm machinery)	1	II	Production manager of engine & machinery (1)	Semi-structured interview; seven occurrences, 1 for each participant Validation of conceptual, axiomatic model of a machine tool's energy states	Yes
B	Industrial conglomerate (industrial automation)	1	II	Sustainable production engineer, corporate technology researcher (2)		No
C	Semiconductors & Semiconductor Equipment (integrated circuits)	1	II	Energy manager, production engineer (2)		No
D	Machinery (Industrial machinery for automotive)	1	II	Head of advanced engineering, Plant manager (2)		No
E	Commercial Services & Supplies (e-waste collector)	1	III, VI, VIII,IX	Plant manager (1)	Observation (1) Enabling data collection: facility operations data.	Yes
F	Electronic Equipment, Instruments & Components (technology distributor)	1	III, VI, VIII, IX	CEO, Operations manager AI-developer (3)	Observation (1), focus group with 2 participants (CEO and operations manager), and semi-structured interview (1 with operations manager) Enabling data collection: data on working technology prototype	Yes
G	Metals and Mining (Stone)	1	IV	Experienced operators (3)	Observation (2) Semi-structured interview (1) Collecting empirical data on quarry operations	No

[6] Global Industry Classification Standard.

Company no.	Industry (GICS[6]) and main product	RQ no.	Paper no.	Company role and no. of participants	Data collection method and purpose	Conducted by this researcher?
H	Machinery (starch moulding equipment)	2	V, VII	General manager, marketing manager, Pacific area Production manager (3)	Observation (1), semi-structured interview (1 for each participant) Collection of empirical data on sustainability strategy and capabilities for sustainable manufacturing	Yes
I	Machinery (Construction machinery and heavy trucks)	2	V, VII	CEO, production manager, engineering design manager, accounting manager, HR manager (5)	Observation (1), semi-structured interview (production manager only) Focus group (1 with all participants) Purpose as above	Yes
J	Life Sciences Tools & Services (Prescription glasses)	2	V, VII	R&D and operations manager (cross-functional role) (1)	Observation (1), semi-structured interview (2) Purpose as above	Yes
K	Transportation infrastructure (ship repair)	2	VII	Vice director HSEQ manager (2)	Observation (1), Focus group in “unstructured format”. Purpose As above	Yes
L	Transportation infrastructure (ship repair)	2	VII	3D scanning technology practitioner, maintenance director (2)	Focus group Purpose as above	Yes
M	Marine (Cruise ships)	2	VII	Head of R&D, sustainability manager, UX sustainability designer, PLM implementation lead (4)	Observation (1), semi-structured interview with UX sustainability designer (1) and with PLM implementation lead (1), focus group (3) Purpose as above	Yes
N	Commercial Services & Supplies (End of life services for electronic waste)	1	NA	Senior environmental manager (1) European director (1)	Observation (1) Structured interview (1) Providing key data for environmental impact analysis	Yes

Methods of primary data collection for validation purposes

Surveys

Surveys (Fowler Jr, 2013) were used to validate three solutions which were "good candidates" for inclusion in the assessment framework. In *Papers III* and *VI*, two surveys aimed to collect feedback on a proposed method, by using four multiple-choice questions. The survey questions can be found from page 141 on. For the assessment tool described in the working *Paper VII*, the survey was not to be deemed a data-collection strategy but a platform for implementing the tool itself in the "real world". Instead, the data collected for developing the tool came from the interview data. The collection strategy for this (focus groups and in-depth interviews) has been described before. Since the survey questions were all answered, the respondent is asked three questions at the end of the survey about the usefulness of the tool itself, given the results (sustainability *readiness score*) immediately produced by the software Qualtrics (Qualtrics, 2019). Due to impediments caused by compliance with the General Data Protection Regulation (GDPR) (GDPR, 2019), it was not possible to send the survey for *Paper VII* to a wider external audience in the manufacturing industry's top management as initially planned. Instead, it was restricted to a small number of project participants in the Ecoprodigi project (Centrum Balticum Foundation, 2019). The survey in *Papers VI* and *VII* were powered by Qualtrics, whereas in *Paper III*, a survey was used which involved a simple table for completion and dissemination via email.

Focus group with unstructured interviews

A preliminary version of the tool (specifically, the second of the four tools presented in this thesis) in *Paper VII* was presented during an informal seminar to two researchers in sustainable operations management, which may be designated a focus group. Their roles were Associate Professor and Post Doc at Chalmers University of Technology. The discussion took place according to an unstructured-interview format (Bryman and Bell, 2011), raising questions on the applicability of the tool (such as the platform to which it could be applied) and the readability of some concepts (which might have sounded overly "academic" to manufacturing management). This focus group allowed this researcher to transfer the tool from hard copy to a digital version in Qualtrics.

The validity of the method presented in *Paper V* (still addressing RQ2 as in *Paper VII*) was challenged in the exact same setting. Specifically, three experts in industrial sustainability were given an unstructured interview: two experts face-to-face and one by an exchange of emails mediated by a common contact. Their expertise covered sustainable procurement, sustainability education in engineering, and business administration. However, giving feedback on a method proved to be more challenging (and in some instances confusing) for the interviewee discussing *Paper V*, than giving feedback on a tool (*Paper VII*).

Methods of secondary data collection (literature)

This section starts with an overview of the secondary data used; the "raw material" of the final body of knowledge presented in Chapter 2. On rare occasions, reports from management consultancies (mainly McKinsey and Deloitte) and science and research magazines (such as the Harvard Business Review, AAAS Science) were used to retrieve secondary data. In the vast majority of cases, peer-reviewed scientific publications were the sources of this secondary data. Google Scholar and Scopus were the databases searched.
The methods with which publications were sought and critically analysed varied according to the goal and scope of the paper being written by this researcher (Elder and Paul, 2004). Furthermore, a variety of literature search methods were used for each paper.
It was noted that the main journals issuing relevant publications were: Business Strategy and the Environment, Ecological Economics, the Journal of Business Research, the International Journal of Production Research, the Journal of Cleaner Production, Sustainability and Waste Management. In some cases, peers, supervisors and mentors directly suggested specific articles.
Certain academic conferences proved to be a good platform for scouting relevant contributors and contributions. The conferences which this researcher most frequently attended were production-related and organised by the International College for Research for Production Engineering (French name: College International pour la Recherche en Productique or CIRP). In particular, the CIRP conference on Manufacturing Systems (CMS) (*Papers IV* and *VI*) and the conference on Life Cycle Engineering (LCE) (*Papers V* and *VIII*).

3.2.3. Data analysis

This section reports the methods of data analysis.

Methods of quantitative data analysis – primary data

Methods of analysing quantitative data are "embedded" in the specific pieces of software used. Because a simulation approach was used in *Papers I* and *III*, data was processed using the AnyLogic software (Version 7.1.2–University) (AnyLogic, 2019). Furthermore, "back of an envelope" calculations were made in an Excel spreadsheet to assess the plausibility of the results. Calculations were based on the application of factory physics laws (Hopp and

Spearman, 2011) for inputting data and key parameters. It is important to note that this researcher did not build the simulation model from scratch; the simulation model was built by the second author of *Papers I* and *III*. This researcher customised the model according to the precise inputs and parameters she collected, designed the experiments and analysed the output results (such as cycle times, energy consumptions).

In *Paper IV*, XML-based software developed by NIST was used by the main author of the study to implement a standard for data characterisation of the production system. It is important to note that this standard was not adopted for pure data categorisation purposes, but mainly for data analysis. Moreover, this researcher was not the direct user of the XML-based software; it was the first author of *Paper IV.*

Quantitative data needed for the LCA analysis of emergent production technology (optical sorter of e-waste) was analysed using OpenLCA software (version 1.4.1) (openLCA, 2019) which used data from the EcoInvent database, version 3 (Ecoinvent, 2019a). This used data from the EcoInvent database, version 3. Details of the research methods adopted for quantitative data analysis can be found in *Papers I, III* and *VI*.

Methods of qualitative data analysis - primary data

When a structured combination of the qualitative data was necessary, the written interview data was synthesised via textual data coding (Weston et al., 2001). Methods of data analysis for inductive and deductive coding are described by Lapadat (2010). This researcher assumed that cases not requiring formal coding procedures were studies dedicated to developing key performance indicators (Study 1 and to some extent Study 2, both for RQ1) which still required qualitative data to make the model design accurate and relevant.

Axiomatic design was adopted as a theoretical background for one of the tools in this thesis (novel energy efficiency KPIs in *Papers I* and *II*). The model's configuration underpinning the KPIs implicitly served to filter and cluster qualitative interview data.

When coding was needed, different approaches were adopted according to the purpose of the study and existence of a suitable qualitative codebook (Creswell, 2009) used by other researchers. It is noteworthy that across the appended publications, interview data coding was done manually in all but one case. Only in *Paper XI* was coding done via online qualitative data coding software Dedoose (Dedoose, 2019). Intercoder agreements were established in *Papers XI* and *XII* only. In *Papers V* and *VII* (both answering RQ2), this researcher worked alone on data coding.

Deductive coding was adopted when a qualitative codebook already existed and fitted the purpose of the study. Deductive coding was adopted in *Paper V*, to characterise a property of "complexity" in capabilities for sustainable manufacturing. The qualitative codebook used was an adaptation of one by Segalàs et al. (2008) and Segalàs (2009). They characterised the complexity in defining sustainable development from the textual data of several concept-mapping workshops. Furthermore, or *Paper V*, it was clear that study participants who described their strategy for sustainable manufacturing were referring the scope of the product's supply chain. This was actually an inductive realisation born of the interview data. This researcher subsequently interrogated the data by asking "what is the extent of the product's life cycle (in other words, the life-cycle thinking of management when describing their manufacturing capabilities)?"

With this question in mind, codes of the life cycle's scope became obvious, incorporating the words "material extraction, "recycling and "remanufacturing", as illustrated in *Paper V*. Hence, an interplay between deduction and induction took place in the data analysis process for answering RQ2.

Grounded (inductive) coding was used when comprehensive information about the phenomenon was needed from the data itself (given the inputs from the study participants in RQ2). This happened during the first round of coding the interview data; data used to develop the tool to measure organisational readiness for sustainability (published in *Paper VII* and originating in Study 4.1).

Indeed, this researcher began her exploration for RQ2 equipped with an existing conceptual model: NIST's sustainable manufacturing maturity model from Mani et al. (2010). This was a mediating object for the first round of interviews and focus groups in Study 4.1. The study participants were actually asked to use the conceptual model to "place their company's sustainability maturity" on one of five levels of maturity, based on a description for each one. The reactions of the study participants in this endeavour formed the qualitative data collected in each intermediate version of the model. Naturally, using such a mediating object frames the data coding, effectively making it deductive. Each new version of the model (which later became the organisational readiness tool for sustainable manufacturing) was the result of lessons learned from the previous trials of it in industry; three in total. Inductive coding was only used when new elements arose.

Data collection for the development of a solution for RQ2 was deemed "saturated" (Charmaz and Belgrave, 2007) with six company cases (at least for a first working version of the solution, which was implemented in a tool-like format).

Methods of qualitative data analysis - secondary data

In general, there were three stages in the literature analysis for the whole body of knowledge relevant to this research. At this first stage of literature analysis, the search started with a set of queries combining key words and Boolean operators connecting those words. Title, key words, abstract, conclusion and graphical elements of the retrieved publications were skimmed to assess in binary fashion (yes/no) the relevance of the publication and its eligibility to the intermediate stage of analysis.

In the second stage of literature exploration, each PC folder which stored potentially interesting publications actually contained 50% to 200% fewer publications than the number in the first stage. The publications excluded from the second stage of literature search were still kept in a separate sub-folder. The total number of publications included in the second stage of literature analysis (across all the topics of interest) was 479. The conceptual map in Figure 23 on page 132 represents those 479 publications. They contributed to an initial understanding of the body of knowledge illustrated in Chapter 2.

Query configuration (in other words, the keywords and the combinations of keywords through Boolean operators) was progressively fine-tuned as this researcher learned to ask questions of the database which would produce a list of increasingly relevant publications compared to the ones previously retrieved.

In the third stage of analysis, covering the 479 publications, 18% of them (85 publications) made a major contribution to the development of the results in this research. This means that these publications are either included in the reference list of appended papers (*Papers I to XII*) or that they contributed to a deeper understanding of the research field after they were issued.

As mentioned in Section 2.3, no study or part of a study undertaken by this researcher was devoted to the production of a systematic literature review.

3.2.4. Overview of data collection and data analysis methods per paper

Table 4 (on the next page) illustrates several information pertaining the research methods adopted in each of the core papers, from *Paper I* to *Paper VII*.

Table 4: Classification of the core publications: RQ and research-methodology related dimensions.

Paper #	RQ	Role of paper in the research process	Research methodology's features in paper	Methods and techniques for data collection in paper	Methods and techniques for data analysis in paper
I	1	*Tool application:* Application of tool developed in Paper II which led to development of a novel indicator. The indicator "breaks down" the leading energy inefficiency factors in production systems	• Deductive reasoning • Axiomatic approach (conceptual modelling of CNC machine state) • Quantitative research • Individual case study in a simplified discrete event simulation (DES) environment	Observation of operating CNC machines	DES software: AnyLogic. Version 7.1.2–University One-tailed test for validating statistical significance (ANOVA) Histograms
II	1	*Tool development:* Measurement model for energy efficiency of machine tools for energy management purposes	• Abductive reasoning (inductive→deductive→inductive) • Conjunction of empirical approach (interviews from six company cases) and axiomatic approach (conceptual modelling of CNC machine state) • Mixed-methods research, mostly quantitative	Observation of operating CNC machines Semi-structured interviews in six company cases, with eight interviewees in management positions	Synthesis of interviews and follow-up with member checking
III	1	*Method development:* Development of a "proto-framework" version of the framework for sustainability assessment proposed in this research and targeting RQ1 Expansion of analysis scope: from Paper I and Paper II's scope (machine tool or	• Abductive reasoning, (inductive→deductive→inductive) • Empirical study • Mixed-methods research, mostly quantitative • Individual case study in Sweden • Proof of concept (demonstrator) of a technology for production systems	Facility walkthrough Structured interview for quantitative data collection via Excel sheet form (input data to simulation)	DES software: AnyLogic Version 7.1.2–University Life cycle assessment (LCA) screening with OpenLCA software (v 1.4.1) EcoInvent database (v3)

Paper #	RQ	Role of paper in the research process	Research methodology's features in paper	Methods and techniques for data collection in paper	Methods and techniques for data analysis in paper
		simple lines made by machine tools) to Paper II's scope (production system)		Two semi-structured interviews for qualitative data (e.g. operator procedures, WEEE Directive's shortcomings)	
IV	1	*Method application:* Support for every possible answer to RQ1, data-wise: manufacturing process data characterisation for performance environmental analyses	• Inductive reasoning • Empirical study • Mixed-methods research • Individual case study in Sweden	Interviews with three operators and site visits in three quarries in Sweden. Data on internal logistic processes As per standard representations ASTM E3012-16 (WK35705, 2014)	Demonstration software with XML syntax Value stream mapping "upgraded" with unit manufacturing process (UMP) representation
V	2	*Method development:* Opening the prospect of a new research question (RQ2) Development of sustainable manufacturing capability mapping (taxonomy) and sustainable manufacturing capability maturity	• Abductive reasoning • Empirical study • Qualitative research • Case study research methodology • Multiple case study in Australia in three SMEs	Factory walkthroughs Six in-depth semi-structured interviews using a protocol A focus group of six people (not same as above) in top management positions Interviews with three corporate sustainability management experts (outside company cases)	Interplay between a-priori and grounded coding.
VI	1	*Method development and application:* method proposed in the paper was developed and applied in the WEEE ID	• Deductive reasoning • Empirical study • Quantitative research • Individual case study in Sweden	Structured interviews for quantitative data via Excel sheet form	Life cycle assessment (LCA) screening with OpenLCA software (v 1.4.1) EcoInvent database (v3).

Paper #	RQ	Role of paper in the research process	Research methodology's features in paper	Methods and techniques for data collection in paper	Methods and techniques for data analysis in paper
		project and applied again in the ReSmaC project. Publication refers to application of method in WEEE ID project only Application in ReSmaC was used as validation via report and follow-up survey		Semi-structured interviews for qualitative data (same as Paper III)	
VII	2	*Tool development and tool application:* Zooming in on the methodology developed in *Paper V* by extending a branch of it. Note: as this thesis goes to press, Paper VII has not been not published and is being submitted for peer-review.	• Abductive reasoning • Empirical study • Qualitative research • Case study methodology • Multiple case studies in Australia, Sweden, Lithuania, and Finland	Factory and shipyard walkthroughs In-depth interviews and two focus groups in six company cases with total of 17 interviewees Online documentation and information on companies	Interplay between a-priori and grounded coding. The validity of the emerging themes was checked in the literature.

3.3. Interpretation and synthesis

In qualitative research, Creswell (2009) named the process of synthesising research studies to build theories "holistic account". He states that a possible output of a holistic account is "a visual model of many facets of a process or a central phenomenon [which] aids in establishing this holistic picture". This is the case for the assessment framework produced at the end of this research.

From a methodological standpoint, the interpretation of the individual research outputs results used six guiding questions. These were applied to help select solutions developed in the research studies and mark them as key components of the framework. The six questions were:

1. Was the proposed solution peer-reviewed by the scientific community?
2. Was the proposed solution validated by potential users?
3. Did the proposed solution add value, when compared to one or more similar sustainability assessment solutions already in practical use?
4. Can an approximate time of use for the proposed solution be estimated?
5. Can the extent of resources needed to use the proposed solution be estimated?
6. Does the proposed solution sync with another, previously selected solution included in the framework?

It is a truism that ideally, a "yes" to all six questions should exist for every tentative solution that selected as a key component of the framework. However, the effort was directed at incorporating and connecting those solutions with the highest number of "yes" answers possible, whilst addressing the research questions. As solutions were added, connected and excluded, notes and drawings were made in a notebook to represent the latest outlook of the assessment framework. However, this process saw three major iterations and no small number of difficulties in synthesis and interpretation.

3.4. Criteria for research quality

Research quality criteria differ according to the type of data which builds scientific knowledge. In particular, Guba (1981) referred to two different research quality concepts: the concept of "rigour" for the case of the rationalistic (which he also labelled "quantitative") paradigm and the concept of "trustworthiness" as the parallel term for "qualitative rigour". A parallel between the two concepts is shown in Table 5 on the next page. Definitions are given for each concept.

Table 5: Parallels between the scientific and naturalistic terms appropriate to the four aspects of trustworthiness. Adapted from Guba (1981).

Scientific term	**Naturalistic term**
Aspect 1: Truth value	
Internal validity	**Credibility**
"Internal validity is logically determinable by demonstrating isomorphism or verisimilitude between the data of an inquiry and the phenomena those data represent - not an unreasonable expectation when one begins with an assumption of a single reality upon which inquiry can converge"(Guba, 1981).	"The extent to which a research account is believable and appropriate, with particular reference to the level of agreement between participants and the researcher" (Mills et al., 2010).
Aspect 2: Applicability	
External validity, generalisability	**Transferability**
"Generalizability requires that the inquiry be conducted in ways that make chronological and situational variations irrelevant to the findings" (Guba, 1981).	"The degree to which the conclusions can be applied to other entities or settings"(Teddlie and Tashakkori, 2003). Simply put, this is the transferability of the results.
Aspect 3: Consistency	
Reliability	**Dependability**
Reliability is concerned "with issues of consistency of measures" (Bryman and Bell, 2011).	The stability of the data and the extent to which changes occurring in context of the study can affect conduct of the research. Dependability also relates to "the trackability required by explainable changes in instrumentation" (Guba, 1981).
Aspect 4: Neutrality	
Objectivity	**Confirmability**
"An investigation of this world is considered objective if the process and results are unbiased; that is, undistorted by the particular dispositions of and the particular situation surrounding the investigator" **(Smith, 1983b)**.	A situation in which steps have been taken "to help ensure as far as possible that the work's findings are the result of the experiences and ideas of the informants, rather than the characteristics and preferences of the researcher" (Shenton, 2004).

Table 10 in Appendix D (page 137) reports tactics suggested by scholars of research methodologies to ensure research rigour and trustworthiness. Each group of tactics refers to a quality criterion illustrated in Table 5

4. Results

"Whatever creativity is, it is in part a solution to a problem."

Brian Aldiss (1925 -2017)
Science fiction writer

4.1. An Assessment Framework for Managing Corporate Sustainable Manufacturing

This research began with the aim of developing an assessment framework for corporate sustainable manufacturing. From a theoretical standpoint, the assessment framework is a *conceptual framework* which the management of manufacturing companies uses to *think* about *how* to measure the economic and environmental performance of its production systems. This research does not prescribe what to measure, but suggests how to measure what a company deems relevant (or "material") to the overall sustainability performance of its organisation. However, given the global concern about CO_2 emissions from industrial activities, part of the assessment framework focuses explicitly on the energy efficiency of machining operations and uses the global warming potential indicators for technology assessment applications. From a practical standpoint, the assessment framework embeds research-based "solutions" to measure sustainability performance and impacts of production systems in manufacturing companies. These solutions have been developed by this researcher over five years of research into sustainable manufacturing, based on 14 company cases.

Figure 11 illustrates an assessment framework for managing corporate sustainable manufacturing. The assessment focuses on production systems.

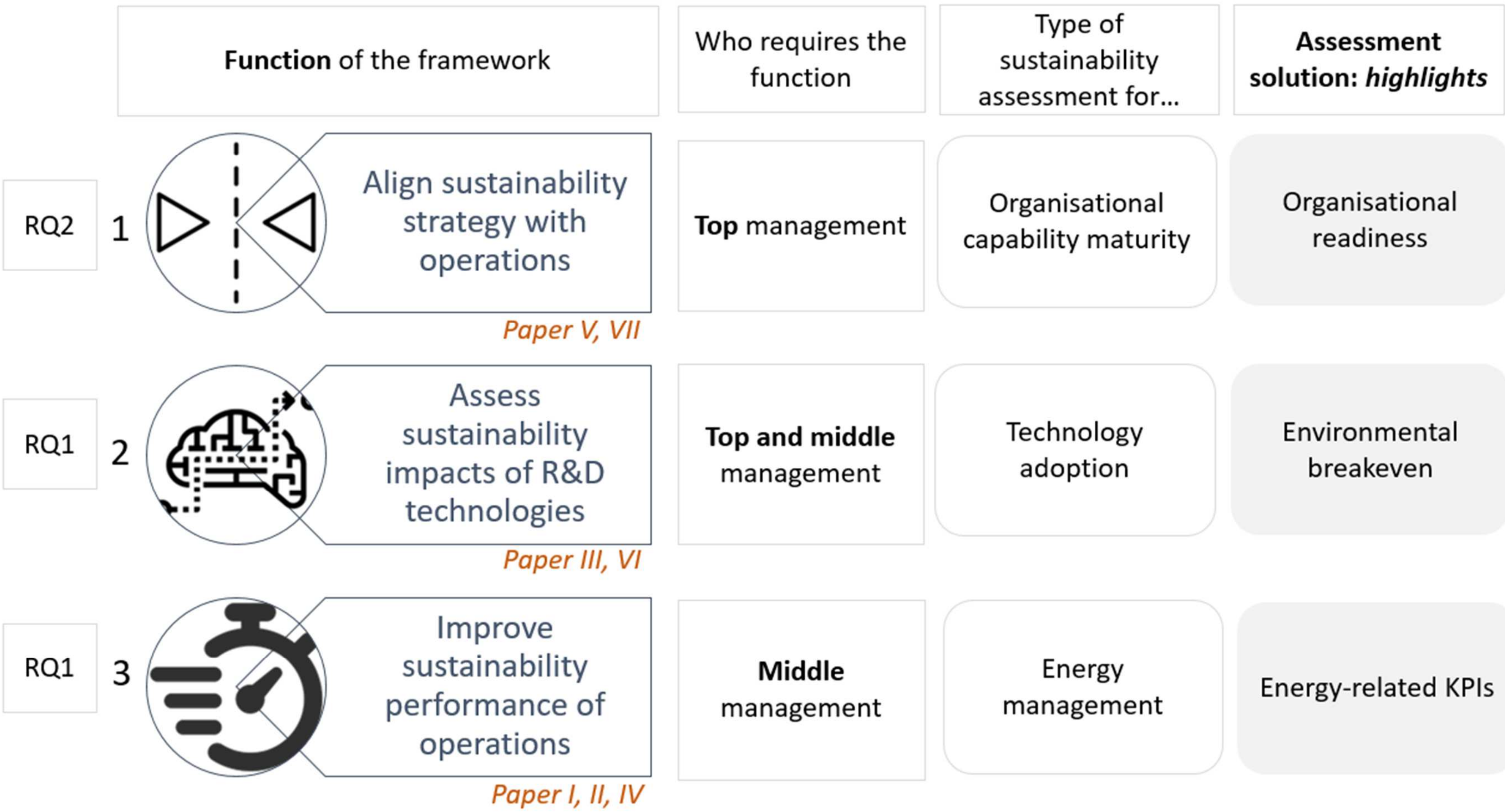

Figure 11: Assessment framework for managing corporate sustainable manufacturing.

This researcher developed an assessment framework for corporate sustainable manufacturing by synthesising and connecting the core research outputs (*Papers I to VII,* published or summited for review 2014-2019).

Support to management is provided by three different functions of the framework (see Figure 11): 1) alignment between sustainability strategy and operations, 2) assessment of R&D technology to ensure positive environmental return and 3) improvement of the production system's economic and environmental performance.

The first function is enabled by assessing the *readiness* of the organisation to build or continuously improve the maturity of manufacturing capabilities which the company considers "core" to realising its sustainable manufacturing strategy. The first function aims to answer RQ2.

The second function ensures that management can see the production point at which an emerging R&D technology reaches a point of neutrality/break-even in regard to the environmental impact category the company considers relevant. The third function enables continuous improvement of environmental performance via an enhanced data-driven approach to performance measurement: firstly, KPIs for monitoring operational causes of energy inefficiencies in machining and secondly, standardisation efforts on data to represent a manufacturing processes and measure operational and environmental performance.

Matters of strategic alignment will probably be tackled annually by top management and encompass the whole organisation.

At the other extreme of the framework, the operational improvements function got third place, as its operational decisions at factory and machine-level are made in the short-term. In the case of energy efficiency, this may range from monthly to quarterly. Middle management would be the user of the third function. The second function, focusing on technology assessment and its sustainability impacts, was "conveniently" placed in the middle layer of the framework. It is actually difficult to estimate the frequency with which a certain manufacturing company would need to use this function. Its frequency of use would depend on the capital intensity and "innovation intensity" of the company. Moreover, another reason for technology assessment having second place is because it involves not only top management (given the investment choice to be made) but also middle management (as potential user of the technology). Hence, function 2 represents a junction between top and middle management.

From the perspective of the "logic" sequence between the different functions of the framework (as opposed to a sequence commanded by frequency of use), the framework's functions should be used in the order: 1, 3 and 2.

Moreover, strategic alignment presupposes that a decision on what and how to measure manufacturing operations' sustainability performance has been made. In turn, the decision

to upgrade a production system with a novel piece of technology would come from an awareness of the current sustainability performance of the production system.
The user of the assessment framework user would exploit the most telling function in a current problem/situation. He/she would therefore "pick and choose" the methods and tools according to the specific problem at hand while maintaining the underlying message of the framework as a substrate throughout the different types of assessment.
The assessment framework does not figure as "proprietary". In fact, company management can fill/enrich the framework with sustainability assessment solutions currently used by the company. Doing this allows management to find negative redundancies between them and pinpoint the input data needed to make any individual assessment worthwhile and fruitful.
The core message of the assessment framework is that it forces management to be aware of and consider sustainable manufacturing performance improvement at a production system level by identifying the links between sustainability strategy (as explained by sustainable manufacturing capabilities) and sustainability performance indicators and impact indicators.

The remaining part of the chapter sees each function exploded into the following structure: management level demanding the function, level of analysis (machine tool until organisation), input data needed, problem to be addressed (formulated as use case) and suggested methods and tools to purse a possible solution. Each of the appended papers explains the outlook of each possible solution in their results sections.
From an academic perspective, a "solution" may be seen as a scientifically developed method for solving a problem. More specifically, a "solution" includes what this research has defined as "method" and "tool". This researcher established a convenient difference between the two as follows: for a method to be used in industrial practice, external specific competences and expertise might be required. However, it is assumed that a tool may be used in industrial practice with no intermediary.

4.2. Function 1: align sustainability strategy with operations

The profile of this first function of the assessment framework is:

- who demands the function: top and middle management;
- level of analysis: organisation;
- input data needed: sustainability strategy, capabilities for sustainable manufacturing and type of key performance indicators of interest;
- use case (problem) - mismatches between sustainability strategy and production operations. Examples of problem statements from the top management of manufacturing companies are:

> *"We do not have a sustainability strategy deliberately implemented in production, or at the very least declared in words and shared among stakeholders".*
>
> *"We strive to reduce waste in production, but we do not see how more demanding incremental environmental efforts would benefit the business strategy and bottom line to the same extent".*
>
> *"We do not know if we are able to implement the sustainability strategy, given our current management practices and choices of resource allocation. We wish we could quantitatively grasp the quality of our management choices in terms of resource allocation with respect to our sustainability goals".*

- *Papers V* and *VII* contain a method and a tool respectively, which contribute to solving the problem.

4.2.1. Method 1: capability methodology for sustainable manufacturing– Paper V

The Capability Methodology for Sustainable Manufacturing (CMSM) in (Barletta et al., 2018a) is a method supporting the answer to RQ2, focusing on strategic alignment. The term "capability" (coming from management theory) is central to this method. The study was initiated by asking interviewees which manufacturing capabilities would support their sustainable manufacturing strategy. The following instances were stated by the focus group in Company M (indicated as "Company A" in *Paper V*). Company M is a shipbuilding company based in Turku:

- transparency and awareness of parts network,
- keeping up with new technologies for machines, within and outside of the factory,
- improving internal efficiency and quality,
- supporting machine owners in the product use through apps and digital tools.

As the study progressed, this researcher understood how the terminology used to describe both capabilities and sustainable manufacturing strategy was highly indicative of management's understanding of sustainable development as concept. To unravel this understanding, the complexity-scope matrix was developed, based on the coding of interview data. The C-S matrix in Figure 12 shows four distinct archetypes of formulation and, consequently, development of a sustainable manufacturing strategy.

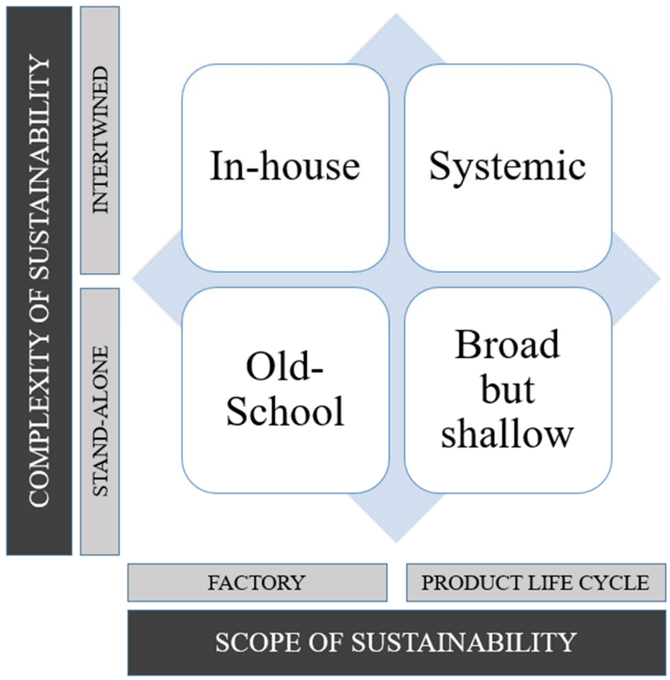

Figure 12: Complexity-Scope of the Product Life Cycle (C-S) matrix used to classify the archetype of strategy development for sustainable manufacturing. From Paper V: Barletta et al. (2018), p. 246.

Each archetype resulted from the intersection of the two dimensions of analysis: complexity of the concept of sustainable development (as analysed by Segalàs et al. (2008)) and the scope of the product life cycle which the company is considering. For more details, please see pages 245-246 of *Paper V*. Even though the complexity level must be identified by adopting the aforementioned coding system, the C-S matrix can be used "unofficially" by management to swiftly identify their archetype and any desired future one. For the cases of Companies H and I, the sustainability strategy boiled down to the most familiar principles of quality management and eco-efficiency: doing more with less, in terms of material and energy. With reference to Figure 12, both Companies H and I seemed to start in the "Old-school" quadrant and end up in the "In-house" quadrant.

The CMSM was developed at the end of the studies conducted in Companies H, I and J. The CMSM is divided into two phases (Figure 13).

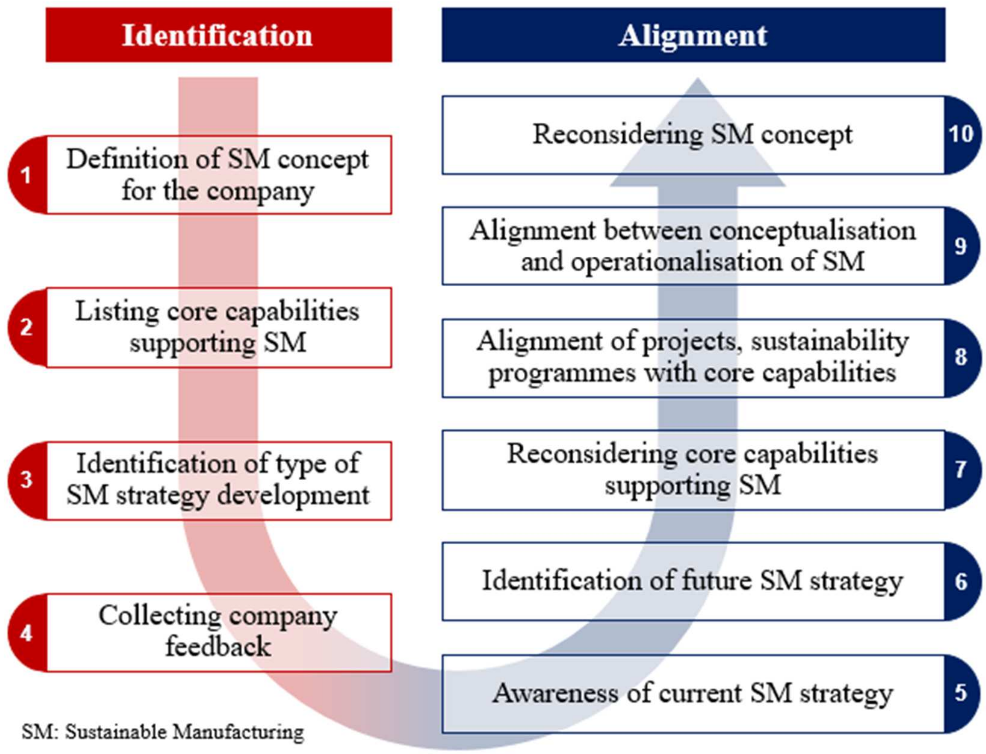

Figure 13: Phases and steps of the Capability Methodology for Sustainable Manufacturing. Revised from Paper V: Barletta et al. (2018a), p. 245.

Steps 1-4 correspond to the identification phase, in which management specifies the current sustainable manufacturing strategy. Steps 5-10 correspond to the alignment phase, in which previously identified gaps are addressed. The identification stage corresponds to the part of the CMSM on data collection and analysis and run by the analyst operating the CMSM. The alignment stage corresponds to the company's use of results from the CMSM. Given the distinction between "method" and "tool" established in this document, the CMSM qualifies as a method. Indeed, for some companies, executing some of the steps may be laborious and require additional external support. For instance, the C-S matrix (Figure 12) becomes a tool exemplifying Steps 3 and 6 of the CMSM methodology. The production manager of Company I commented on the misalignment experienced by his company. The following is an extract from a written communication by the production manager of Company I:

"We need to move further into the product life cycle. As a manufacturer and supplier, the position of selling premium products for good profit has long gone, with our competitors now matching our strength in this field, and thus dropping profits to low levels. To continue in business we need the focus to shift to 'whole-of-life' (…)"(Barletta et al., 2018a).

Although it may appear that the *systemic* archetype in Figure 12 is the most favourable one for promoting the vision of this research, a discussion with two experts in manufacturing strategy concluded that this might not always be the case. Indeed, a company may have run successful sustainability-oriented projects, programmes and initiatives in quadrants other than the systemic one, in the short term. However, the systemic archetype is arguably the most desirable quadrant to occupy in the long-run by individual companies and manufacturing as a whole.

4.2.2. Tool 1: organisational readiness assessment for sustainable manufacturing - Paper VII

The question answered by the organisational readiness assessment tool in *Paper VII* (Barletta et al., -) is: what are the key factors, in production systems that contribute to a manufacturing organisation's sustainability readiness?" This question is a question deriving from RQ2. An organisational sustainability readiness tool was developed in a questionnaire in Qualtrics (Qualtrics, 2019), comprising 12 questions and taking 10 minutes at most to answer. At the beginning of the questionnaire, the respondent is asked to enter the most important capability for sustainable manufacturing prioritised by his/her organisation. Examples of capabilities for sustainable manufacturing are provided in the questionnaire and include: zero-waste production, pollution prevention, material recovery, cost-effective remanufacturing, rapid and virtual prototyping of products, design for reuse. The organisational sustainability readiness model is applied to one sustainable manufacturing capability at a time.

The organisational readiness tool is based on a scale of four levels of readiness, as shown in Figure 14 on the next page. These levels illustrate a *crescendo* of management practices, as well as management's resource allocation decisions in several organisational systems: manufacturing processes, assets, materials, data-driven decision support tools, information systems and organisational competences. The questionnaire tool helps fulfil Step 8 of the Capability Methodology for Sustainable Manufacturing (*Paper V* – previous section).

Figure 14: Outline of the organisational sustainability readiness model and graphical representation of resulting readiness score. From Barletta et al (-) under review.

From a modelling perspective, the readiness scale (level 0 – level 3) comes from the well-known "traditional" models of capability assessment. The *crescendo* is determined by the fact that adopting a certain management practice (indicated in a given cell of the table) produces economic and environmental performance higher than the one in the cell to its left. The measurement that "represents" the readiness level of the organisation (in other words, the readiness of all the systems in Figure 14) is the "organisational sustainability readiness score" reported in *Paper VII.*Questions and multiple-choice answers are provided here for the "Data-driven decision support" system (Table 6 on the next page). The remainder of all the questions in the questionnaire can be read in *Paper VII*.

Data-driven decision support: *this section relates to the role of data in decision-making which includes sustainability considerations. […] Examples of data-driven decision-making tools for sustainability are: cost-benefit analyses, environmental footprint analyses and modelling and simulation tools applied to production systems. Select the statement that best represents the situation in your organisation. Only one choice is allowed.*

Table 6: An excerpt of the questions on the organisational sustainability readiness model. From Paper V (under review).

Data-driven for decision-making			**Answer**		
How does management use key performance indicators (KPIs) to track performance in "X"*?	Management does NOT use KPIs to track relevant performance areas	How does management use key performance indicators (KPIs) to track performance in "X"*?	Management does NOT use KPIs to track relevant performance areas	How does management use key performance indicators (KPIs) to track performance in "X"*?	Management does NOT use KPIs to track relevant performance areas
To what degree are decision-making tools adopted by management for "X"*?	NO tools in place	To what degree are decision-making tools adopted by management for "X"*?	NO tools in place	To what degree are decision-making tools adopted by management for "X"*?	NO tools in place

The possible answers (statements in each cell of the table) come from the aggregation and abstraction of interview data from the study reported in *Papers VII*. *Note: "X" in Table 6 represents the capability for sustainable manufacturing previously inserted by the respondent in the online survey tool. The data field "X" is automatically populated by the software.

Once the questionnaire has been fully completed, the higher the resulting readiness level per system, the more a specific system is positively contributing to economic and environmental sustainability performance, given how it is being managed.

4.3. Function 2: assess sustainability impacts of R&D technologies

The profile of the second function of the assessment framework is:

- who demands the function: both top and middle management;
- level of analysis: production system, production development phase. Only production systems which process products at their end-of-life stage (such as sorting and disassembly) were analysed;
- input data needed: bills of materials of products and production equipment, product life cycle inventory data, environmental data of production operations, production systems' operational parameters;

- use case (problem): assessing an emerging technology so that economic and environmental impacts are considered. Examples of problem-statements by top management in manufacturing companies include:

  > *"We wonder if we're missing something as we upgrade our facility with new technology that enables circular economy. What's going to happen in the long run?".*
  > *"This new R&D technology seems good on paper when it comes to recovering material from used products. However, we don't know if the investment will break even, sustainability-wise, as the equipment hasn't been built yet. Furthermore, product input flows come with great uncertainty in terms of volume and grade".*

  Papers III and VI describe two methods (one per paper), providing two possible solutions to the problem.

4.3.1. Method 2: decision support methodology for technology assessment in production– Paper III

A decision-support methodology for assessing, visualising and comparing economic and environmental impacts resulting from a technological change was developed and applied to a facility for e-waste sorting. In Figure 15, "EMS" stands for e-waste management systems and "alternatives" refers to the technological alternatives being evaluated, with the "solution" being the alternative ultimately selected.

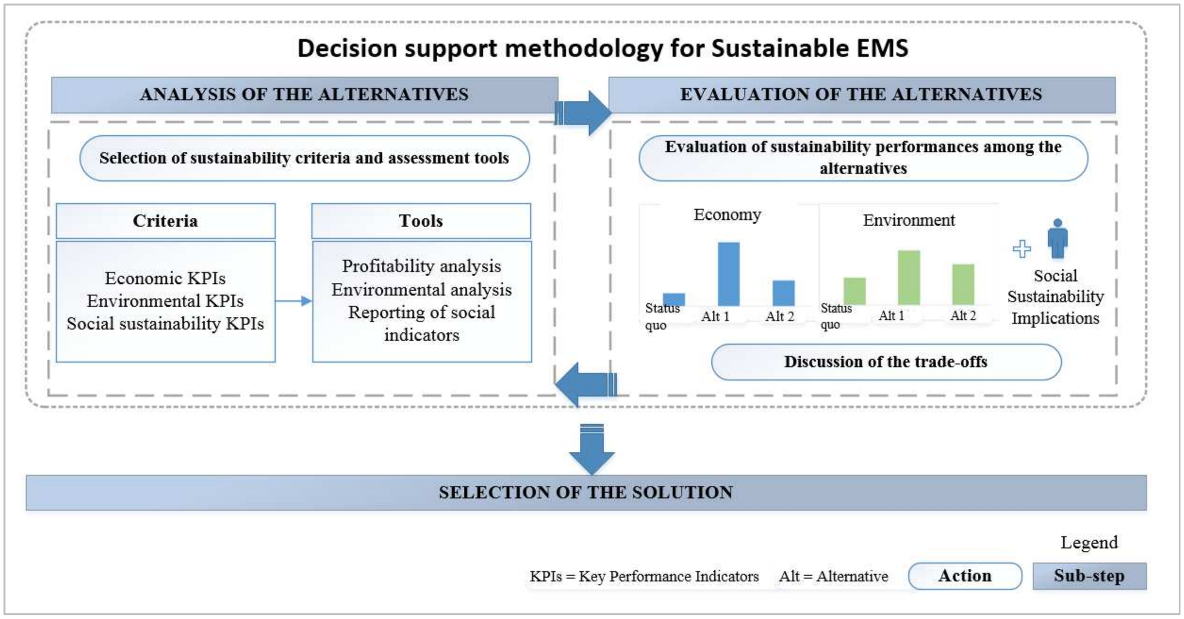

Figure 15: Decision-support methodology for sustainable e-waste management systems (EMS). From Paper III (Barletta et al., 2016) p. 5.

The EMS evaluated in *Paper III* was a facility for manual e-waste sorting, which is considering introducing an optical sorter demonstrator called an e-grader (Figure 16). It uses sensors and intelligent data processing to detect in real time whether used electronic products are suitable for reuse, refurbishment or recycling; it then sorts them accordingly. The demonstrator is programmed to list products in optimal fractions by making them instantly available for trading, either directly with customers or through digital marketplaces.

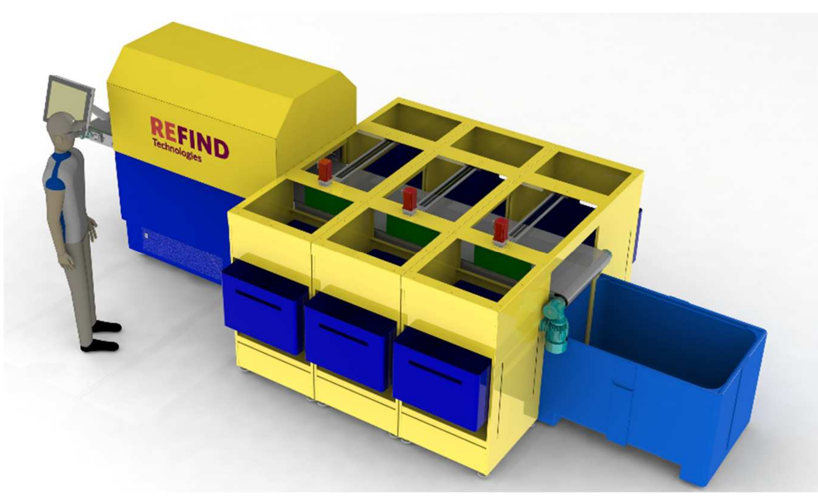

Figure 4: Illustration of the e-grader, developed by ReFind, a company within the WEEE ID project (VINNOVA).

The methods adopted for assessing the sustainability impacts of the e-grader were:

- discrete event simulation (DES). This was applied to calculate the industrial costs and return-on-investment from adopting the e-grader. A virtual model of the facility helps visualise the layout of the facility with the e-grader installed;
- screening LCA to calculate the environmental impact from the building and use of the e-grader;
- stakeholder mapping to represent the extent of influence relationships among key stakeholders (pre-processing facility owners, recyclers and electronic users, among many others).

Details of the results from the case study of the e-grader demonstrator appear in *Paper III*. *Paper VIII* (Barletta et al., 2015) illustrated the prerequisites that paved the way for the development of the method illustrated in *Paper III,* whereas *Paper IX* (Taghavi et al., 2015) focused on social implications from the adoption of the technology.

4.3.2. Method 3. environmental break-even analysis of R&D technologies in production – Paper VI

Environmental cost-benefit analyses are not normally among the core skills of CEOs and production managers, yet these actors often make far-reaching decisions which dramatically affect the environmental performance of the products their companies produce.

Thus, a method to calculate the environmental break-even point (e-BEP) of R&D in emerging production technologies was detailed in *Paper VI*. The method is illustrated in Figure 17.

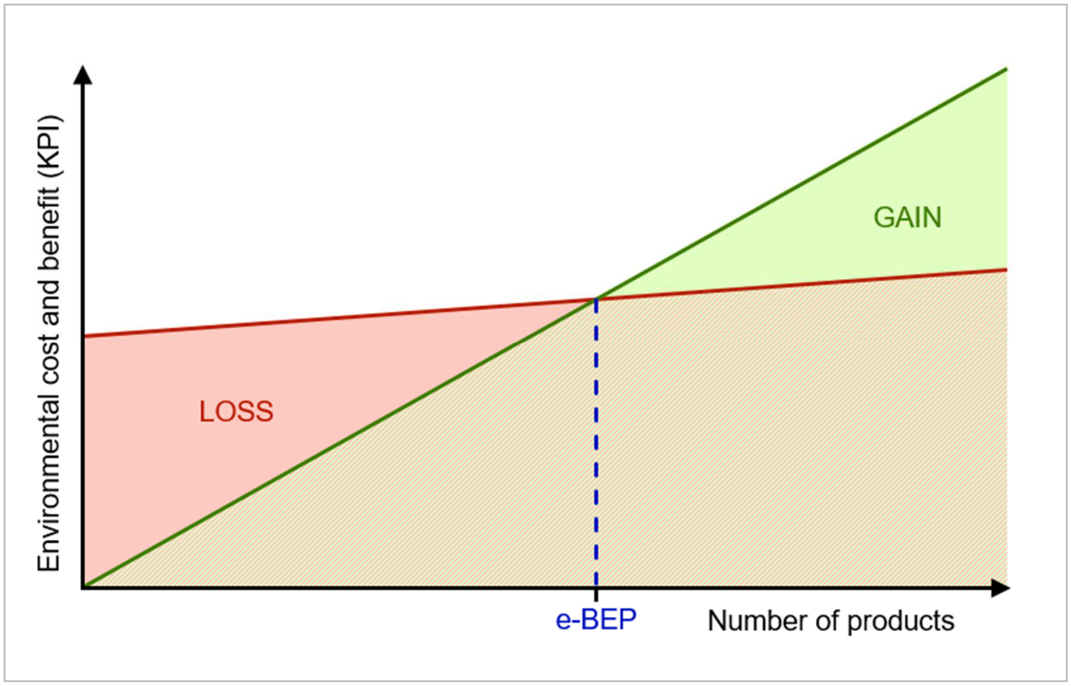

Figure 17: environmental breakeven point (e-BEP). From: Paper VI (Barletta et al., 2018b) p. 722.

The method is well-suited to the environmental assessment of technologies enabling circular economy business models, given the existence of a curve defining the environmental benefits (green line in Figure 17). In *Paper VI*, the production technology being examined was the *e-grader*, mentioned in the previous section.

The e-BEP was defined in *Paper VI* as follows: the number of products being processed by the technology for it to offset its environmental costs against environmental benefits gained from use of the technology during the entire product life cycle. Mathematically, the e-BEP is defined in eq. 1:

$$eBEP = \frac{FEC}{IEB - VEC} \quad (1)$$

Where:
$FEC = fixed\ environental\ cost$
$IEB = incremental\ environental\ benefit$
$VEC = variable\ environental\ cost$

Environmental costs and benefits relate to the environmental impact category required by the goal of the analysis, be it global warming potential (GWP), land use or aquatic toxicity.

For the case of the e-grader, the e-BEP showed production level at which the negative environmental impact from construction and use of the e-grader in a sorting facility is offset by the positive environmental impacts brought by product end-of-life treatments, as opposed to mere recycling (which would have been the default option in manual sorting).

It is important to note that calculating the incremental environmental benefits assumes the baseline of an existing production scenario delivering the same function provided by the technology (sorting, in this case), with variable environmental costs. The incremental environmental benefit includes the avoidance of those costs.

Knowing the break-even as a number of products may be not as meaningful to CEOs and production managers as knowing *when* such an offset takes place.

Starting from the e-BEP, it is possible to give time-based information rather than quantity-based information, using eq. 2

$$ePBT = eBEP \times CT \tag{2}$$

Where: $CT = average\ cycle\ time\ of\ the\ produciton\ line$

The e-PBT defines how long a wait is needed, given the production rates, until the technology pays off its environmental burden. It is interesting to compare several e-PBTs (or several e-BEPs), each reporting a different environmental indicator. This allows possible trade-offs to be highlighted.

The e-BEP was developed in the research project involving the e-grader (WEEE ID) (VINNOVA) (*Paper III*) and applied again in another project, ReSmaC, investigating a novel concept product arising from the upcycling of used smartphone components (Chalmers Research, 2018a).

In the WEEE ID project, the e-BEP of the e-grader, in its lite demonstrator version, could be as low as 255 smartphones repurposed instead of recycled. Transports were excluded from the analysis. The e-PBT depends largely on the frequency of replenishment from e-waste collectors to the sorting facility and, naturally, on the quality of input from the e-waste streams.

In the ReSmaC project, the e-BEP was calculated for two types of production facilities and production processes which would realise the conceptual product *Sensei*, a multi-purpose, customisable sensor (BOID, 2019, Chalmers Research, 2018b). The production facility could be set up for small-scale production or mass-production. Furthermore, another contributing "scenario generation" variable was the type of product system which each incremental unit of Sensei would have replaced in the market: a baby monitor in one case and a tablet-based smart home security system in another. Comparing all the scenarios in respect to their global warming potential, the best-case scenario resulted in a Sensei substituting a smart security home system and produced on a small scale. In this case, Sensei pays off its environmental burden after its first six months on the market, given the rough estimate provided by the original equipment manufacturer (OEM). Sensei would start adding environmental benefits from the 1133rd unit that was sold. The external logistics of e-waste collection to and from the production facility were not considered.

4.4. Function 3: improve sustainability performance of operations

The profile of this third function of the assessment framework is:

- who demands the function: middle management;
- level of analysis: machine tools and production systems;
- input data needed: machine tools' energy usage, operational parameters of the production system (e.g., production scheduling, line balancing rules);
- use case (problem) 1: need for effective energy management systems in production and need for increased economic and environmental operational efficiency. Examples of problem-statements from middle management of manufacturing companies are:

  > *"At the very best, we know roughly the amount of energy consumption spent per manufactured product in our factory. Given that we will soon have sensors and telecommunication capabilities that track more granular information of our manufacturing processes, we would like to break down our "macro" indicators into some key components to act upon".*

  > *"Even in the case of having key performance indicators to track, we don't know how to test them and use them systematically for energy efficiency purposes".*

- use case (problem) 2: need for standardised environmental data on (and a shared language of) manufacturing processes to identify performance improvements. Examples of problem-statements from middle management of manufacturing companies are:

  > *"We don't use a shared language to describe the environmental sustainability data of our manufacturing processes. Our information systems represent them differently. As a result, tracking and discussing improvements of manufacturing processes across the board is problematic".*

- *Papers I and II* contain a similar kind of tool and *Paper IV* a method.

- All of them are focused on energy-related aspects of production activities. *Paper I, Paper II* and *Paper IV* are in scope of the assessment framework and therefore are illustrated in Section 4.4.1 and Section 4.4.2. The reader who would like to know about the link between operational and social performance areas is invited to read *Paper XII* (Pinzone et al., 2018), whose results are beyond the scope of the assessment framework.

4.4.1. Tool 2: energy-related KPIs for energy management– Paper I and II

The interpretation of cause-effect relationships between events of production systems operations and energy consumption is a key aspect of effective energy management. From an academic standpoint, *Paper II* (May et al., 2015) offered a seven-step method to develop energy-related key performance indicators (e-KPIs) which would serve this purpose. This method supports the identification of weaknesses and areas for energy-efficiency improvements related to operations management in production. From the middle management perspective in a manufacturing company (energy manager, production manager for example), an indicator developed through the above method should be highlighted: the Lean Energy Indicator (eq. 3).

$$Lean\ Energy\ Indicator = \frac{\sum_{i=1}^{n}(P_{processing\ i} \times Q_{good\ i} \times T_{processing\ i})}{Energy\ consumed\ in\ theoretical\ production\ time} \tag{3}$$

where:

$T_{processing\ i}$ processing time of the piece “i” in the product mix

$P_{processing\ i}$ average processing power demanded by the piece “i”

$Q_{good\ i}$ quantity of saleable pieces of the piece “i” in a certain time horizon

Eq. 3 shows that the Lean Energy Indicator represents the ratio between energy consumed in making saleable products and the overall energy consumption of the machine over a certain time. The Lean Energy Indicator aims to show how efficient the equipment is in terms of energy consumption. For the production manager or energy manager, the goal is to use energy more efficiently for production of one saleable output. For this reason, the closer the Lean Energy Indicator is to 1, the better. Thanks to the methodology developed in *Paper II*, several mathematical equations were developed which break the lean energy indicator into different components, each addressing different management practices in production. The Lean Energy Indicator results from eq. 4:

$$Lean\ Energy\ Indicator = E_{opening} \times E_{usage} \times E_{avail.} \times E_{sat.} \times E_{quality} \quad (4)$$

where:

$E_{opening}$ assesses the impact of post-holiday or post-shift machine start-ups

E_{usage} assesses the impact of causes at overall system level and not strictly at machine level

$E_{avail.}$ assesses the impact on time spent on maintenance activities and break-down times

$E_{sat.}$ assesses the unsaturation of the machine due to a series of events which slow down production of the resource (in the time available), such as minor stops and setups

$E_{quality}$ assesses the energy wasted due to quality problems

The mathematical equations of each constituent in the multiplication appear in Paper II. Another example of e-KPI, the energy overall equipment effectiveness (energy OEE) indicator, was proposed and tested via a DES model in *Paper I* (Barletta et al., 2014). Figure 18 depicts the "building blocks" of the indicator; in other words, the different types of energy consumption which fall into the equation of the indicator (eqs. 5 and 6):

$$Energy\ OEE = E_{availability} \times E_{performance} \times E_{quality} \quad (5)$$

$$Energy\ OEE = \frac{Operating\ Energy}{Loading\ Energy} \times \frac{Theoretical\ Energy\ Consumption\ for\ Q}{Operating\ Energy} \times \frac{Q_{nd}}{Q} \quad (6)$$

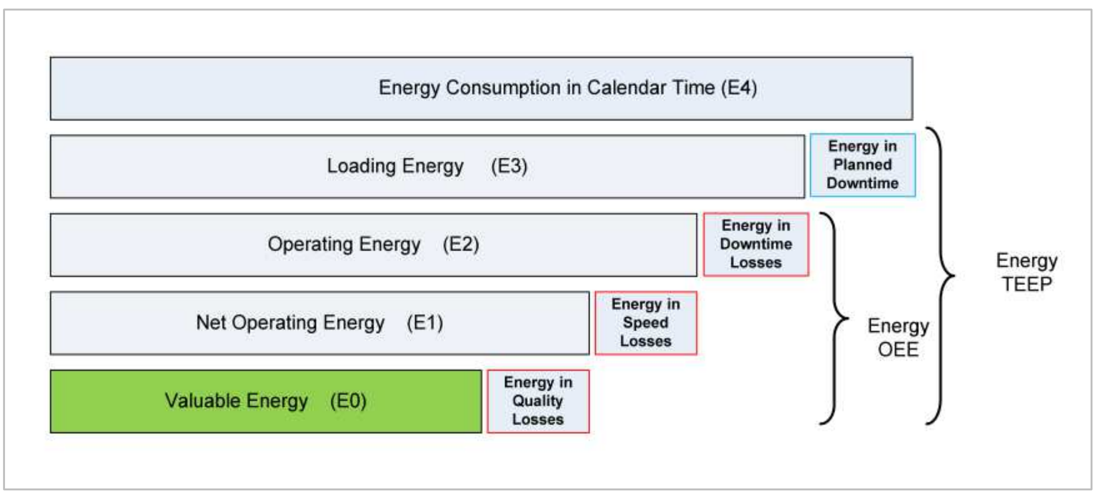

Figure 18: Energy Overall Equipment Effectiveness Diagram. From: Paper I, (Barletta et al., 2014), p. 1101.

Details about the mathematical equations that constitute the Energy OEE can be read in Paper I, p. 1101-1102.

Figure 18 shows how the energy OEE is the energy-based equivalent of the well-known time-based version of overall equipment effectiveness, stemming from the pioneering work of Nakajima (1988) in founding the philosophy of total productive maintenance.
The e-KPIs which comprise the lean energy indicator (an e-KPI itself) and the energy OEE allow easy identification of areas for intervention and responsible actors within the production system. For example, a low value of $E_{avail.}$ compared to other indicators $E_{opening}, E_{usage}, E_{sat.}, E_{quality}$ suggests a need for intervention in the maintenance function. Once an action plan has been drawn up, the improvements are visible in the reduced energy consumption and related CO_2 emissions. The usefulness of the e-KPIs can be boosted in a simulated environment, as shown in *Paper I*. Indeed, in a simulation environment, sensitivity analyses can be conducted across the range of minutes and impacts compared across scenarios.
The energy consumption matrix illustrated in Figure 19 guides the development of an improvement plan in terms of energy management.

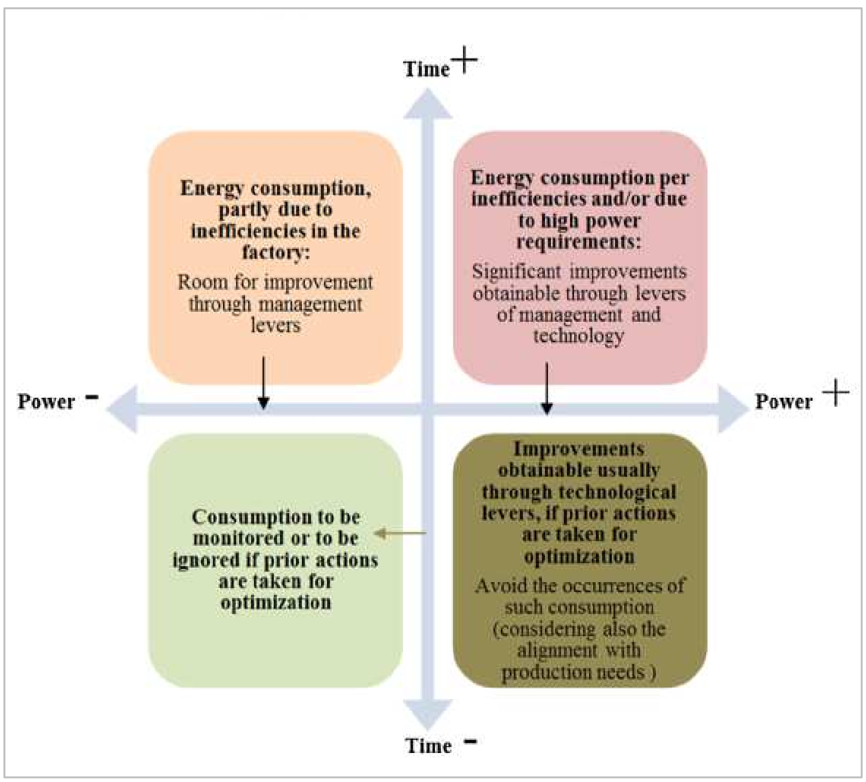

Figure 5: Energy consumption matrix for decision support. From Paper II, (May et al., 2015), p. 57.

The matrix includes two dimensions: the horizontal dimension represents the magnitude of the individual energy consumption (such as power required for the machine's ramp-up phase). The vertical dimension represents the time in which the single power requirement has been observed in the monitoring time T (such as the number of ramp-ups x the single ramp-up time). Ultimately, *Paper II* advises on actions which are doable for each quadrant, from an energy management perspective.

4.4.2. Method 4: characterisation of environmental data of manufacturing processes – Paper IV

Although standards for business-process modelling do not constitute a sustainability assessment method per se, they allow relevant performance areas of manufacturing processes to be computed. *Paper IV* (Rebouillat et al., 2016) saw testing of the ASTM standard E3012-16 “Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes” (Mani et al., 2012, Mani et al., 2014, WK35705, 2014) in the case of a quarry for natural stone production. The guide outlines a characterisation methodology and proposes a generic representation from which manufacturers can derive specific unit manufacturing process (UMP) representations. The guide treats UMPs as a shared foundation of sustainability performance analysis.

Inputs to UMPs include materials and consumables; product and process information includes process specifications, production plan, equipment specifications, material specifications, and so on; resources include equipment/tooling, software and so on. Outputs include products, by-products and waste.
Transformation may include material transformation (such as mass change, phase change, structure change, deformation and consolidation), energy transformation (including chemical, electrical, thermal, mechanical, and electromagnetic) or information transformation (such as production metrics, including throughput and overall equipment effectiveness) and environmental metrics (such as energy, material, water, emissions and waste). The quarry case studies analysed block formatting and internal logistics. The processes underlying fuel and water consumption were characterised and modelled by defining the transformation equations. An XML-based software demonstrator tool was used to operationalise the standard.
Unfortunately, not all the necessary data to determine fuel consumption (internal logistic operations) and water consumption (used in quarrying operations) was available in the quarry case studies. This hindered the possibility to obtain numerical results from the model composition of the series of UMPs that were connected, both graphically and formally.
However, the absence of this data did raise awareness within management of the very need for collecting this kind of environmental information.

To sum up, four methods and two tools are the key components of the assessment framework for corporate sustainable manufacturing. All its tools and methods contribute, to varying extents, to better informed decision-making aiming to increase economic and environmental performance of a manufacturing company.

5. Discussion

Half a truth is often a whole lie.

Benjamin Franklin (1706 – 1790)
Polymath

Section 5.1 comprises an assessment of the quality of this research, given the criteria of rigor and trustworthiness.
Section 5.2 describes the setting whereby some of the tools and methods have been externally validated.
Section 5.3 highlights ethical issues in the conduct of the research.
Section 5.4 illustrates how the assessment framework answers the research questions, in terms of contributions to knowledge and limitations. Specific components of the framework are pointed out in some cases.
Section 5.5 answers the question "is the use of the assessment framework able to champion the realisation of the vision of a sustainable manufacturing industry?"

5.1. Evaluating the research quality of the assessment framework

Table 7 (on the next page) reproposes the research-quality criteria, already illustrated in Chapter 3, and applies them to the evaluation of the quality of the assessment framework from the perspective of rigor and trustworthiness.

Table 7: Evaluation of the quality of the assessment framework from the perspective of rigor and trustworthiness.

Scientific term	Naturalistic term
Aspect 1: Truth value	
Internal validity	**Credibility**
NA. Reason: testing this criterion does not suit the very nature of the assessment framework, whose nature is qualitative.	High credibility. Reason: from moderate to high level of communication between participants and this researcher. All the 12 publications but one have been published in peer-reviewed conference proceedings or journals.
Aspect 2: Applicability	
External validity, generalizability	**Transferability**
NA. Reason: as above.	See Section 5.2 "Validating transferability" on page 92.
Aspect 3: Consistency	
Reliability	**Dependability**
NA. Reason: as above.	Low dependability. The duration of each study per company case did not last for more than a year and a half (max). Significant changes can happen in this time frame. Some companies were going through technological and managerial changes, which were tracked in the data collection. Thick descriptions of the case studies in the paper, descriptions of the methods of data collection and data analysis secure a decent level of trustworthiness with respect to dependability.
Aspect 4: Neutrality	
Objectivity	**Confirmability**
NA. Reason: as above.	Low confirmability. Having the full corpus of the collected qualitative data being coded by other researchers via a software would have secured higher confirmability. Having the study participants from the industry interacting with a sustainability researcher may have conditioned the veracity of empirical data shared for the studies run for RQ2.

Table 7 is an example of an evaluation which is expected to be shown for a case study based research targeting management. It follows that Eisenhardt and Graebner (2007), when illustrating the challenges that building theories from case studies entail, provide a good template for constructively highlighting the challenges that this researcher has tried to overcome. Though it must be said that their paper is dense with many more valid points for the planning stages of case-study based research, rather than the evaluation of it. However, for the sake of brevity and effectiveness, only a couple of points will be presented in this paragraph, as the rest is considered more suitable for a live or offline discussion with this researcher herself. Moreover, some of the points raised by Eisenhardt and Graebner (2007) were tackled in Section 3.2.1 (when it comes to the "theoretical" sampling of cases". A first point that Eisenhardt and Graebner (2007) asked to focus on is research questions. "The challenge of justifying inductive case research partially depends on the nature of the research questions […]Typically, the research question is tightly scoped within the context of an existing theory, and the justification rests heavily on the ability of qualitative data to offer insight into complex social processes that quantitative data cannot easily reveal" (Eisenhardt and Graebner, 2007). Unfortunately, observation of company cases all took place on a single occasion. This researcher believes that richer data useful in building the assessment framework might have been collected with multiple, longer observations. Issues about the lack of inter-coded qualitative (across several researchers) may also affect the fit that the data had in unveiling a possible answer to the RQs. An intriguing trade-off that Eisenhardt and Graebner (2007) presented is the one between the "richness" (lack of "parsimony") of a theory from one side and the robustness and generalisability of a theory on the other side. This researcher believes that the theoretical intake (and therefore output) of this research is rich, multi-faceted, and therefore lacking of parsimony and conciseness. This poses applicability challenges (because of poor robustness and generalisability) that are discussed in Section 5.5 (A critical view of the assessment framework) and more precisely in Table 11 on page 138 (Appendix D).

Table 8 on the next page illustrates a self-evaluation of the quality of this research, given the criteria contained in Table 5 and existing tactics in Table 10. Table 8 illustrates the evaluation of specific methods and tools that are part of the assessment framework, as opposed to referring to the assessment framework as an individual entity (done instead in Table 7)

Table 8: Evaluation of this research's rigor and trustworthiness, according to methods and tools developed.

	Quality criterion	Method/tool in the assessment framework for which the criterion is especially relevant	Research quality tactics adopted	Instances of the tactics in the research studies
Quantitative paradigm	**Internal validity**	e-KPIs: Lean energy indicator (*Paper II*) and energy OEE (*Paper I*)	Logic model	Peer-reviewed conceptual modelling and testing in a DES environment. A statistical significance analysis followed
	External validity	NA	NA	No quantitative single or multiple case study research was carried out for theory-building purposes
	Reliability	Energy OEE (*Paper I*) Environmental break-even analysis (*Paper VI*)	Case study database Note: basic information about the quantitative analysis of case studies in the appended papers does <u>not</u> qualify as case study protocol, but more as procedural outline, with some activities emerging as the study went along	Experiments and preliminary results arranged in files and calculation sheets. Input parameters to simulation runs are indicated Reliability of data input depends on reliability of the data as collected and classified in the Ecoinvent database (*Paper VI* only)
	Objectivity	e-KPIs (*Papers I* and *II*) Environmental break even analysis (*Paper VI*)	NA	Motivation: the studies are based on conceptual modelling or adoption of methods from another field with no aim of proving specific hypotheses. Objectivity results from the tactics illustrated above

	Quality criterion	Method/tool in the assessment framework for which the criterion is especially relevant	Research quality tactics adopted	Instances of the tactics in the research studies
Qualitative paradigm	**Credibility**	Decision-support methodology for technology assessment in production (*Paper III*) Capability methodology for sustainable manufacturing (*Paper V*) Organisational readiness assessment for sustainable manufacturing (*Paper VII*)	Prolonged engagement	Email communications and participation in consortium meetings, so as not to "lose touch" with the context of company cases
			Member checking	Participants (any industrial "data providers") were asked to check the preliminary findings and narrative account of project deliverables and publications
			Triangulation	Data collected through multiple methods are compared and combined to locate major theme and eliminate overlapping areas. (*Paper VII* only)
			Peer scrutiny	Discussion of the study's method and findings at a scientific conference and seminar (*Paper V* only)
			Ensuring honesty in informants	Voluntary participation and termination of the study.
	Transferability	Decision-support methodology for technology assessment in production (*Paper III*) Capability methodology for sustainable manufacturing (*Paper V*)	Refuting evidence through questionnaire or open-ended questions	Probing questions were asked about the usefulness and applicability of the tools/methods in the real world. Respondents were managers in the manufacturing sector.

Quality criterion	Method/tool in the assessment framework for which the criterion is especially relevant	Research quality tactics adopted	Instances of the tactics in the research studies
	Environmental break even analysis (*Paper VI*) Assessment of organisational readiness for sustainable manufacturing (*Paper VII*)		
Dependability	Characterisation of environmental data from manufacturing processes (*Paper IV*) Environmental break-even analysis (*Paper VI*) Assessment of organisational readiness for sustainable manufacturing (*Paper VII*)	Reporting on data-gathering and interview protocols	Reporting of collected data in meeting minutes, project deliverables, standard templates in Microsoft doc and Powerpoints, shared via email
		Prolonged engagement	Email communications and participation in consortium meetings so as not to “lose touch” with the context of company cases (*Papers VI* and *VII* only)
Confirmability	Capability methodology for sustainable manufacturing (*Paper V*) Organisational readiness assessment for sustainable manufacturing (*Paper VII*)	Statement of researcher’s beliefs and assumptions	As this researcher became familiar with each company’s participants, assumptions and background, the definition of her research was shared with them (such as sustainable manufacturing, triple bottom-line)
		Triangulation	Data collected using multiple methods is compared and combined to locate major themes

Quality criterion	Method/tool in the assessment framework for which the criterion is especially relevant	Research quality tactics adopted	Instances of the tactics in the research studies
			and eliminate overlapping areas (*Paper VII* only)

5.2. Validating transferability

A research-validity test was not applied to the whole assessment framework, due to difficulties designing a validity test suitable for testing the framework "in the real world". Ideally, the framework could have been tested in an individual company using, say, a longitudinal case study. Ideally, such a case study would fulfil the following requirements:

- a sufficiently long test time for a company to use all (or at least some) of the framework's methods and tools;
- detection of any improvement to environmental and economic performance unmistakably *triggered by use of the framework.* This point would be extremely hard to prove, given exogenous contextual factors of a company business (such as macro-economic fluctuations, sudden scarcity of material) which also affect its sustainability performance. Indeed, the proposition under which the framework might have been tested would relate to its perceived usefulness, rather than a measurable effect on the company's sustainability performance.

This lack of longitudinal, holistic validation also stems from the fact that the framework came about as a synthesis of five years of research efforts.
Most importantly, it is no coincidence that the framework was designated as such rather than as a "toolkit". Its main purpose was to guide management in tackling the unsustainability challenge from within the company, counting on its agency and ability to make better decisions for sustainable development. Questions about the transferability of some of the tools and methods of the framework "in the real world" were obviously raised and required legitimate testing, given that this research work has been practice-oriented. In this sense, the test phase of the tool/method coincides with its validation. The components of the framework eligible for validation were:

- organisational readiness assessment for sustainable manufacturing (Function 1, *Paper VII*)
- decision support methodology for technology assessment in production (Function 2, *Paper III*)
- environmental break-even analysis of R&D technologies in production (Function 2, *Paper VI*)
- energy-related KPIs for energy management (Function 3, *Paper I* and *Paper II*)
- characterisation of environmental data of manufacturing processes (Function 3, *Paper IV*).

5.2.1. Transferability of the organisational readiness assessment for sustainable manufacturing (Paper VII)

Five items comprising questions and statements were developed to validate the usefulness of the organisational readiness assessment. The data collection form used for this purpose appears in Appendix E, on page 143. Questions were still embedded in the online survey-tool itself, which implemented the organisational readiness assessment. The questionnaire was sent to 20 professionals in the shipbuilding and ship repair industry who hold management positions relating to product and production development and technology development. Those respondents are partners in a project in which this researcher participated, Ecoprodigi (Centrum Balticum Foundation, 2019).

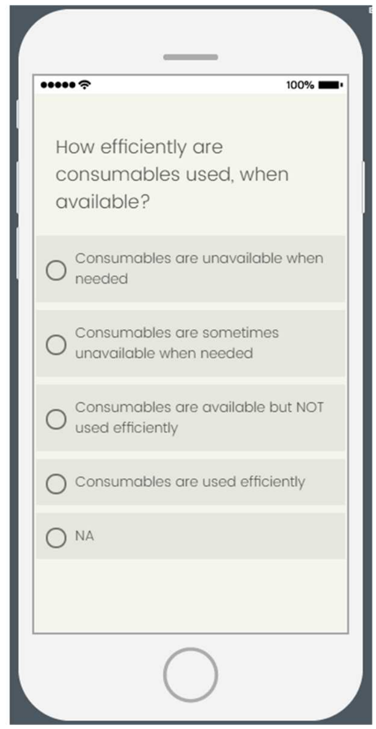

Figure 6: Online questionnaire interface in Qualtrics, shown from a mobile device.

Figure 20 shows the user interface for the questionnaire appears as seen on a mobile device. Questions forming a core part of the tool were all structured according to the same format seen in Figure 20. The question displayed in the figure belongs to the set of questions within the "material management" system. At the end of the questionnaire, the respondent can see the results and his/her company's readiness score and receives a full report of the results in a PDF file. He/she is then asked about the value of the questionnaire itself, based on the information shown in the results. Naturally, a substantial and diverse group of roles within a given company must complete the survey for the aggregate of the survey results to be truly representative. Unfortunately, this scenario (aggregation of a "large enough" number of multiple-choice responses per company) did not happen. Only six people responded to the survey (a response rate of 30%), meaning that the results of the internal validity test cannot be trustworthy.

However, having said that, disclosing the reactions of the respondents after completing the questionnaire is still worthwhile. Five respondents answered "somewhat agreed" with respect to the statement "these results suggest the priorities to tackle by management for increased sustainability performance". Four respondent answered "somewhat agreed" with respect to the statement "These results suggest a course of action for increased sustainability performance". For those who did not find the results helpful, their perspective was reflected with “The answers to the questions did not describe the situation of my company”. This raises a point on the extent to which it is possible to claim that any discrete manufacturing company manager would be a good candidate for using the tool.

When reflecting on the 30% response rate, this researcher had the impression that surveys are seen as a time-consuming, exercise, overused (and abused) by professionals, especially when the survey promises results which might be helpful to the company.

It was also impossible to carry out an external validity test, as initially intended. This researcher prepared a respondent distribution list of 74 contacts from different avenues: research projects, personal contacts and common networks (such as Production 2030). However, as it turned out, this researcher was unable to use the list as pool of respondents. Financial risks of conducting the survey under the general data protection regulation (GDPR) exceeded the benefits of validating the tool.

On an anecdotal level, a supply-chain management consultant of the Finnish firm Sininen Polku Oy, a member of the Ecoprodigi project, commented on the usefulness of the organisational readiness tool as a template for interviews within projects that address sustainable operations. This was a use that this researcher did not contemplate as an alternative. The interview for which the manager used the model was with several suppliers of Company M on questions about interoperability of ICT systems across the value chain from the perspective of sharing operational (at a logistics level) and product environmental data and information. The management consultant was familiar with the second version of the model underneath the assessment tool. The consultant claimed that the matrix-shaped model helped him to ensure that all the areas that he deemed relevant to be covered were indeed covered.

It should be noted that the organisational readiness tool was a key component of the set of guidelines for strategic alignment that were presented in *Paper V* and illustrated in Figure 13. The set of guidelines was developed thanks to Company H, I and J, from which some comments - mixed in reaction - on the guidelines were collected. Unfortunately, it was not possible to test it in any of the companies that this researcher interacted with afterwards.

5.2.2. Transferability of the decision-support methodology for technology assessment in production (Paper III)

A five-question questionnaire was prepared to validate the transferability of the decision-support methodology proposed in *Paper III*. In October 2015, this questionnaire was emailed to five top-management representatives at five companies within the e-waste supply chain in Sweden and Finland. Appendix E on page 141 shows the data collection form that was used.

The questions dealt with the perceived value of each functionality of the method, including virtual modelling of material flows in the production facility (in this case, an e-waste sorting facility). The questions were meant to be answered by choosing an answer on a Likert scale from 1 (no value) to 5 (very valuable).

Four of the five previously contacted people answered the questionnaire and one respondent added comments. On average, the total perceived value score was 3.7; close to a "valuable" contribution of the method for industrial practice. The standard deviation of the answers was 1.6.

Surprisingly, the functionality which received the lowest score in terms of perceived value was the one using a virtual model of the facility.

The functionality which received the highest score in terms of perceived value was "increased understanding of the key actors in reverse logistics supply chains"; this was actually the least developed functionality of the method, with only a qualitative stakeholder map (Figure 21 from *Paper III*).

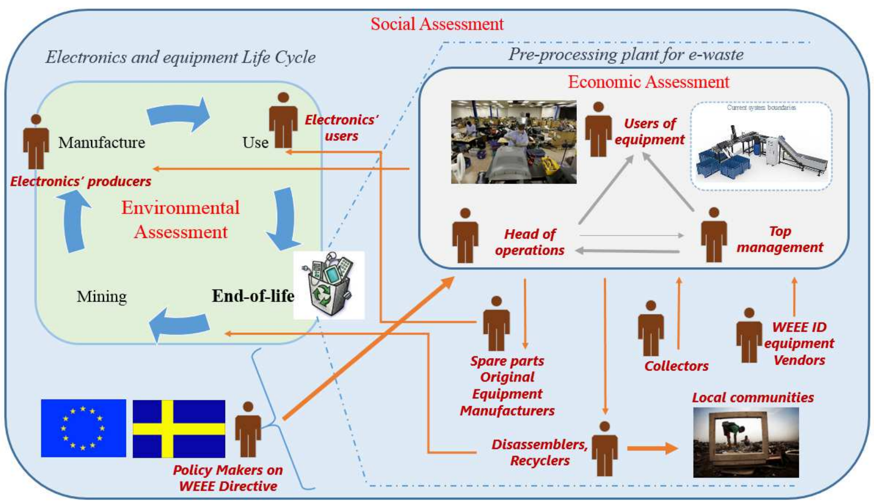

Figure 21: Stakeholder map: influences among stakeholders as part of Method 3. From Barletta et al. (2016) p. 15.

A respondent with a CEO position added the following remark, quoted verbatim:

"From our viewpoint, waste processing is in quite a bit of disruption. Legislation and public opinion is getting stricter, but prices of raw materials are volatile. Old mechanical separation processes can't quite cope with the throughput and purity requirements. It would be therefore very interesting if the rate of change of the waste industry could be somehow quantified. I've heard of multimillion euro plants becoming financially nonviable even before they're completed. Definitions and requirements of fractions seem to be rapidly developing too. So, it'd be interesting to know things such as how many plant operators have had a significant

demand for new fractions, or thought about investing into more careful analysis of what they actually do, and so on. There's definitely need for better modelling tools for recycling plants, but I wonder how to make the model so that it's concrete enough to give real results, and flexible enough not to become obsolete with new processes".

This researcher agrees with the diagnosis of the problem offered by this respondent. Ideally, the design requirements imposed on novel modelling tools could produce "nearly instantaneous" results, given key input parameters in terms of materiality risks and input waste stream forecasts. This could be implemented in a future software program.

5.2.3. Transferability of the environmental break-even analysis of R&D technologies in production (Paper VI)

A five-statement questionnaire was developed for validating the usefulness characteristics of the environmental break-even analysis in industrial practice. In January 2019, this questionnaire was sent to 102 people, of which 56% held management positions in a manufacturing company, 30% were academics in manufacturing/production research and 16 % were consultants for manufacturing companies. The respondent distribution list resulted from contacts aggregated from different avenues: research projects, personal contacts and common networks (such as Production 2030).

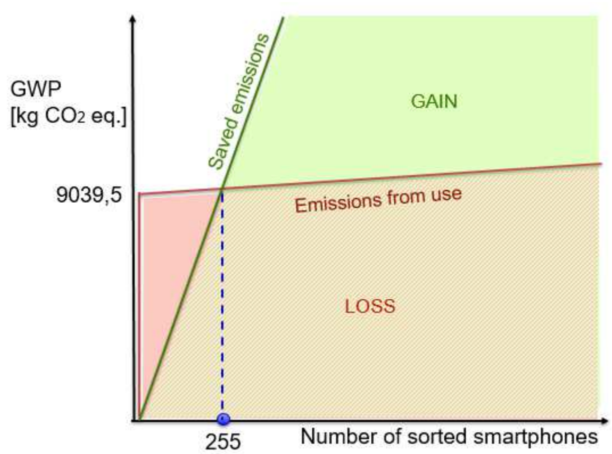

Figure 7: Application of the e-BEP for evaluating the e-grader, an optical sorter for smartphones. Picture presented in the video used for validation and in Paper VI (Barletta et al., 2018b), page 724.

Built on the Qualtrics software, the questionnaire was sent by email. The data collection form used is available in Appendix E on page 142. Before answering the questions, the respondents were asked to watch a video in which the method was explained and a practical example given (Figure 22).

The video is available via this link: https://drive.google.com/file/d/1ruAlgoUU4mDg6T3MgoV23IUE1xQldiw7/view?usp=sharing

The questionnaire took six minutes to complete and was anonymous. Each of the possible answers laid in a five-item Likert scale based on the agreement with a key statement. The extremes of the scale were "strongly disagree" and "strongly agree".
The response rate was 46%, with the following affiliation distribution: 65% industry, 22% academia and 13% other (research consultancies for the most). The answer with higher incidence across the four evaluation questions was "somewhat agree", with percentages as follows:

- 47% for understanding the reason why management would use the environmental break-even analysis,
- 49% for usefulness of the method to management in technology-adoption decisions,
- 49% for helpfulness of the method to management in understanding results from environmental assessments from a combined product and production perspective.

The third group also received the highest number of negative reactions ("somehow disagree" or "strongly disagree" across all statements, with a 7% selection for "somewhat disagree").
A non-negligible 4% "strongly disagree" answer was given to the question about understanding the mechanism to calculate the environmental break-even point.
Unfortunately, because of GDPR compliance, no questions beyond the mere distinction "industry vs academia" could have been asked to the respondent to gain demographic information about his/her role and expertise. This information gap makes contextualisation of the results difficult. Luckily, two respondents added remarks by emailing this researcher after the completion of the questionnaire. Excerpts from these comments have been quoted verbatim.

From a corporate researcher in a large multinational company providing transport solutions, headquartered in Sweden:

"…I'm sorry to say but I'm generally not positive about these kinds of simple evaluation tools (even though I have myself published tools like it but not for environment), so my answers in your survey will be towards the not-agree to the usefulness of it. One loses too much detail and importance of the environmental issue to simplify it to a numerical measure, where one investment option can get '255' and the other '280', and then say that '255 is better, so let's go with that'..."

Furthermore, regarding the decision-making process of the technology evaluation, the respondent added:

"*….I believe the project team then will summarise their recommendations and points for all aspects based on their now deep insight and competence, in such areas as financial, technical,* *risk and environmental, for top management to make a final decision based on these competent recommendations. And in this process, I don't (yet) see where your tool will fit. Perhaps even more unfortunately, there are still too many financial people making the final decision, where money talks loudest, and it doesn't seem to matter which tool we use, if the financial break-even is positive on an investment alternative, that's the one which will be selected…".*

From a CEO of a small Australian B2B manufacturing company that produces a niche building material. The CEO has a personal interest in climate issues:

"My biggest issues with the tool are that it relies on comparing, say, the CO_2 price of something with CO_2 savings to work out the payback period. What if the metric changes? As in, what if I am 'spending' water to 'save' CO_2 emissions.... it gets a little tricky as the tool only lets you work with one constant unless you have a conversion factor, which would be different for every situation.
And that's what's cool about the tool I guess.... there are lots of levers you can pull to weight it in different ways. The economic version of the BEA [author's note: break-even analysis] is easy because there is only one variable and that is $$".

The comment given by the first respondent points to the well-known duality between reductionism and holism (and, even more critically, simplism and unnecessary complexity) embedded in the different sustainability assessments that have been published in the literature. Furthermore, the claim about the lack of an influential role of management in decisions which determine the company's sustainability shook the seemingly safe ground for the usefulness of the assessment framework in achieving its aim.
The comment by the second respondent can be broken down into two components:

1. use of the method for one environmental impact indicator at a time, to the exclusion of everything else (unless each e-BEP is calculated for each impact indicator of interest);
2. the point of how environmental impact indicators can be valued (and acted upon) by management when their values express a physical measurement as opposed to a currency which can be inserted into corporate financial toolboxes. This comment is legitimate, especially considering the critical timing of intervention by large multinational companies in environmental issues.

These valuable points have been re-proposed in Section 5.5, page 108.

5.2.4. Transferability of the energy-related KPIs for energy management (Paper I and Paper II)

This section is much shorter than the other 5.2.X series of this chapter. In fact, it is in *Paper I* that a specific type of e-KPI, the energy-based overall equipment effectiveness indicator (EOEE), is shown to have been tested in a DES environment. *Paper I* was presented at the Winter Simulation Conference 2014 held in Savannah, GA, USA by this researcher. At this stage this researcher missed the opportunity to collect feedback from the audience systematically. However, on an anecdotal level, the reception from the audience was generally positive, since both the industrial audience and academic audience were familiar with the time-based version of this e-KPI, which is the overall equipment effectiveness indicator (OEE). Furthermore, the study underneath *Paper I* showed that coding the information that the EOEE summarises in a DES model is easy for any intermediate-to-advanced DES practitioner.

5.2.5. Transferability of the characterisation of environmental data of manufacturing processes – (Paper IV)

In order for the standard to be operationalised, an XML-based software demonstrator tool was used in *Paper IV*. The use of this piece of software might pose some challenges to using the standard when the characterisation is scaled from individual units to a whole production system (system of “composed” and linked UMPs), in instances where the company does not have employees with basic programming competences. The full potential of the standard in terms of process modelling and improvement is only reached at this complex level of characterisation.

In April 2019, this researcher interviewed one of the technical leaders at NIST who was co responsible for the development and research demonstration of the standard guide E3012-16. The interviewee is a systems engineer and researcher at NIST. He shared the news that, in April 2019, a new revision of the E3012-16 passed the vote from the ASTM committee E60 on sustainability. The new version will be published on the ASTM website in May 2019. He showed how significant steps have been made in the use of the standard since its inception dawn in 2016. From a transferability point of view, the demonstrated applications that this researcher deems promising are illustrated in (Bernstein et al., 2018) and in (Kulkarni et al., 2019). In particular, Bernstein et al. (2018) illustrated how the standard enabled the parametric environmental analysis of manufacturing systems “without disrupting the traditional LCA workflow”. The study used the Brightway2 framework (Brightway 2, 2019) to generate a life cycle inventory in ecoSpold2 (Ecoinvent, 2019b). This allowed the authors in

(Bernstein et al., 2018) to perform an LCA on a vertical milling unit process. This application demonstrates that environmental data characterised as per E3012-16 facilitates environmental assessment of manufacturing processes, as it does so according to the established LCA framework and existing databases' structure.

5.3. Ethical conduct of the research work

The main issues concerning ethical codes of conduct in this research boil down to:

1. Transparency in communicating the intent to publish the research studies' results to the industrial project partners.
2. Confidentiality of data shared by industrial project partners (in connection with point 1).

This researcher explained that the contribution to academic knowledge was by no means of lesser value than the contribution to practice. Furthermore, she explained that peer-reviewed publications would have to be issued so that the contribution to academic knowledge could be critically examined and disseminated. To this end, the industrial partners were invited to help write the publications (if they so wished) or at the very least as reviewers. Accordingly, their contribution was acknowledged in the manuscript.

The issue about companies' data confidentiality was discussed with the companies right at the outset. This is evident from Section 3.2.2 Data collection, which states that, on some occasions, recording was not allowed.

Another data confidentiality issue which affected the validity of the research was compliance with the General Data Protection Regulation (GDPR), which affects EU-based participants in research studies

5.4. Summary, contributions and limitations

The assessment framework consists of four methods and two tools arranged in three concentric functions:

1. The first function focuses on strategy and organisational capabilities for sustainable manufacturing which companies aim to build (such as zero waste, product remanufacturing) and offers an assessment tool to diagnose how well existing operations/management practices in production align with the desired capability. Such a "predisposition" to this alignment was defined as "readiness" in this research.

2. The second function encompasses technology assessment of sustainability-related decision-making in production development. This involves answering a yes/no question about the adoption of an R&D technology ostensibly designed for increased environmental sustainability performance.
3. The third function encompasses production operations' monitoring and diagnostic tools though a series of energy efficiency KPIs, or e-KPI. These are fed with real-time or near-real-time data from machine tool operations and then enriched with production systems' scheduling and balancing logic. Visualising the e-KPIs' values implies a review of those operations/management practices and decisions which contribute to the energy efficiency of manufacturing operations.

The developed assessment framework for managing corporate sustainable manufacturing contributes to the substantial and yet expanding corpus of scientific literature of assessment frameworks and tools for sustainable manufacturing, listed from page 22. The framework shares similarities with some extant frameworks on some fronts and differs in others. From a content point of view, the framework distinguishes itself from other operations-oriented frameworks (which constitute the vast majority of the literature being reviewed) by calling for a connection between strategy development, capability maturity (which this researcher defines as "readiness"), production technology assessment, and operational improvement in energy efficiency, when assessing "sustainable manufacturing" in corporate environments. By highlighting a read thread between these elements, the framework aims to support management in their task of measuring sustainable manufacturing by trying to solving two problems: integration of economic and environmental factors for decisions pertaining to production systems development (RQ1), and the problem of strategy-operations alignment affecting corporate sustainability management (RQ2).
The framework has an overarching qualitative nature, as opposed to the prevailing quantitative nature of the extant assessment frameworks. These characteristics make the proposed assessment framework suitable to be considered by industrialists and academia as a set of "guidelines", an "approach", or more preferably, a conveyer of a new mindset to perform and use sustainability assessments and leverage their power for management.

An important limitation of the assessment framework comes from its lack of demonstration as a unified and coordinated entity, as opposed to a separated demonstration of its components in different contexts of industrial practice and application, which ideally should have occurred without the need for any interaction with this researcher. Moreover, this researcher believes that some of the links between the different components of the framework might need validation with a "devil's advocate" approach - in other words, an intention to falsify the validity of those connections. In fact, these links exist on a multitude of abstraction levels from a corporate management standpoint (machine control to organisational strategy). Hence, the coordination in the use of the framework, in its “version 0”, might be problematic and even confusing for its users (management), let alone the attempt to convert the framework into a software application. Given the qualitative nature of the framework, its “materialisation” would rather occur through a visual, storyboard rather than a software, this researcher believes. If this will be the modality of use, the framework could elicit success stories and failure stories that arose from the experience in connecting sustainability strategies with to-be sustainable operations.

On the other hand, the lack of demonstration of the assessment framework in corporate environments might be partially (albeit to a small extent) compensated by the research design choice that this researcher undertook. In fact, the assessment framework has been developed from a bottom-up approach where a multitude of company case studies in manufacturing provided “raw material” to the development process of the framework. Such a design approach fundamentally differs from the design approaches that other academics adopted, which were much more oriented towards a systematic understanding of the extant literature on sustainability assessment tools and towards the final demonstration of their research output in an individual case study. A critical reflection on the design of the assessment framework is illustrated from page 108. A discussion of contribution and limitation per RQ is illustrated in the rest of Section 5.4, starting from the next section.

5.4.1. Answering RQ1

“How can manufacturing companies integrate economic and environmental sustainability factors into their production systems, both in the development and operations phases?”, RQ1 asked.

Manufacturing companies integrate economic and environmental sustainability factors into certain “decision points” which entail changes in production systems’ operational assets (evaluating a novel technology for example) and actual operations (such as production scheduling of machining operations). Integration happens via relevant operational and environmental measurements (KPIs) which managements find understandable and actionable. The “factor” to be integrated refers to the particular performance area or impact which the KPI measures. This research does *not* focus on *what* performance areas related to economic and environmental sustainability have to be measured by a company, but focuses instead of *how well a company can measure what it wants to measure*.

The “KPI-solution” choice results from the research scope being chosen and the theoretical framework of this research work. The analysis of the literature on measurement and assessment tools/methods for corporate sustainable manufacturing unveiled opportunities

to develop not only novel KPIs that would have addressed specific needs (gap 7, gap 8 and gap 9 in Table 1) so far unmet, but also opportunities to support manufacturing companies in the very decision making process that uses those KPIs.
An issue of integration of sustainability in decision making exists also when economic and environmental factors do not point in the same direction straightforwardly. In some cases, economic and environmental KPIs measure values whose “currency” belongs to distinct pools of capital; in other words, economic (monetary) and natural (such as the atmosphere and water systems).
This knowledge (clearly mirroring existing knowledge on sustainability assessment and management) was gained gradually also during the method/tool development process, as distinct from knowledge possibly gained via a systematic literature review. This researcher would stress that what constitutes new academic knowledge also includes the availability of new assessment methods and tools, provided that the value of incorporating them into the literature is mirrored by the practical benefits of using them.

The next section illustrates RQ1’s contributions to knowledge and practice for each of the methods and tools developed.

5.4.2. Contribution and limitations of solutions to RQ1

In the research that was conducted, RQ1 was addressed by developing two methods and a tool for sustainability assessment of production systems.
The two methods are:

- a decision support methodology (a set of methods) for technology assessment. This methodology considers corporate sustainability factors by using KPIs from LCA and process modelling via DES (*Paper III*).
- a guided environmental break-even analysis of an emerging technology (a concept/prototype/demonstrator) in the e-waste sector, in which the technology reportedly provides environmental benefits as well as fixed and incremental environmental costs (*Paper VI*).

The tool comprises a series of KPIs for tracking leading causes of energy inefficiency in operations at production system level and known as e-KPIs.

The two methods apply to the production development stage of a production system, whereas the tool applies to the operations stage.
The two methods measure output indicators against a measurable baseline, represented by an existing production system which delivers the same function as a newly-planned one which

has been upgraded with a novel piece of technology. The values of the same performance indicators are therefore compared between the as-is state of the production system and its potential to-be state, under the hypothesis of specific future scenarios.

The e-KPIs developed were called the “lean energy indicator” and the “overall energy equipment effectiveness indicator”. Both may be broken down into several components for diagnostic purposes. These components relate to a) the soundness of management practices in production scheduling and b) quality management in machining operations, as seen from the energy-efficiency perspective.

The value of individual solutions forming part of the assessment framework and contributing to answering RQ1 is seen from the perspective of the two-fold target audience of this research: 1) contribution to existing research and 2) contribution to practice. In this document, the former refers to the extent to which the contributions bridge the research gaps highlighted in the introductory chapter and frame of reference chapter.

Contribution to research and gaps uncovered:

The decision-support methodology for technology assessment (*Paper III*) and environmental break-even analysis (*Paper VI*) contribute partially to bridging: **gap 2**, attention to process and production systems; **gap 5**, influencing production development process in the early design stage and **gap 10**, understanding sustainability impact from technology born of Industry 4.0). Both methods fall short in addressing **gap 6** (reductionism vs holism as a barrier to transferability) as it was difficult to decide how to navigate this trade off as method design choice. Similarly, **gap 1** is not addressed, as there is no evidence that the assessment framework as a whole can be effectively transferred to industrial practice, irrespective of whether the framework was designed with that intent.

The environmental break-even point may be considered an example of an indicator addressing **gap 8** (an indicator which embeds product life cycle management considerations). However, calculating the environmental break-even point still fails to avoid the “hurdle” of conducting LCA in corporate environments (**gap 11**) and specific in-house competences which industry may lack (**gap 1**). In the case of the e-KPIs, there is potential for them to be standardised and used for internal and external benchmarking (**gap 9**).

Naturally, these contributions still come at the expense of extending the already proliferating area of sustainability indicators for sustainable manufacturing/sustainable production, whose increasingly large and “disorientating” (author’s observation) size was noted by Moldavska and Welo (2015), Winroth et al. (2016), Lucato et al. (2017) and Kianian et al. (2018). This leaves **gap 7** both unaddressed and widened out. The same argument applies to enriching the area of methodologies and tools for sustainability assessment, as indicated by Gibson (2006) Bond et al. (2012) and similarly leaving **gap 4** unaddressed. However, in the specific case of manufacturing sectors, this researcher argues that the problem seems to lie in the shortcomings of applicability of sustainability assessment tools (**gap 1**), rather than their number and variety. Validating the two methods actually raised issues of applicability.

Contribution to practice and practical limitations:

This researcher argues that, as long as the methods and tool bring unique practical insights, then their incremental addition to an already vast area may be justified. The following paragraphs identify potential contributions to practice and, consequentially, account for the limitations from a practical point of view.

It is fair to state that the output information from the developed methods and tools provides fertile ground for informed decisions by management, including energy managers, operations managers and stakeholders involved in technology investment decisions. However, when consequential-style evaluations are made at the design/conceptual stage of a production system, it is crucial to embed a range of plausible future scenarios in the analysis. Besides considering obvious parameters which would make the results highly sensitive (such as the number of cellular phones suitable for reuse in an e-waste stream), this research fell short of embedding a structured scenario-generation approach. Specifically, it lacked integration with ad-hoc methods of scenario planning and economic and environmental risk analyses. These must be included in the proposed framework, so as to support more solid and reliable decision-making.

The roadblocks to full adoption of the methods and tools for RQ1 in the company practice reside in three factors:

1. Non-availability of input-data beyond the company's information system boundaries (such as product life cycle data).
2. Sophistication of information systems (in this case the Supervisory Control and Data Acquisition, SCADA) in collecting and processing data needed to calculate KPIs. In the e-KPIs case, the energy consumption per each operation (or "state") of the machine tools must be known.
3. Need for in-house expertise on factory simulation and life cycle assessment (LCA), or possibility to outsource to professionals with those competences. For example, the environmental break-even indicator is built on a simple formula and easy to visualise, but still requires an analyst to gather life cycle inventory data and the ability to use a piece of LCA software. Simple-to-use software (such as ready-made applications which a company can easily customise for its needs) and open databases would greatly facilitate broad, scalable practice of this research in industry.

Once these roadblocks are overcome, the use of methods and tools presented above can contribute positively to sustainable manufacturing. Nevertheless, there would still be a great need to integrate methods and tools from additional research areas, such as those excluded from this investigation.

When illustrating the contributions/limitations to practice, it is important to remember that both methods do not prescribe a defined set of performance indicators for the particular case studies (e-waste sorting facility), or for sustainable manufacturing generally. However, in some instances, specific indicators are implicitly prescribed by a clear goal statement in the analysis. For instance, a wish to assess climate implications demands calculation of the global warming potential (GWP) indicator. A "prescription" to use certain indicators which emerged during the studies was instead about the need to make trade-offs emerge by using specific indicators. For the case of environmental analyses, the use of the environmental break-even point (e-BEP) would imply a calculation of one e-BEP per relevant life cycle impact assessment indicator (such as GWP and aquatic toxicity potential) AND for each relevant production parameter which changes the outcome of the analysis (such as mass production vs small-scale production). In the above example, four possible permutations of the e-BEP would need to occur.

By way of example, consider two alternative technologies: one which saves electricity consumption vs another which, thanks to a small piece of wastewater treatment equipment, decreases water pollution. The assumption here is having a budget which allows the selection of only one alternative.

The expectation to find one "optimal" technology alternative from among several alternatives would require a different, and possibly more arbitrary, approach than the one adopted by the e-BEP as used. This different approach entails normalising the impact indicators. Indeed, in relation to the previous example, where GWP and aquatic toxicity potential are two indicators in trade-off, the analyst would need to come up with an equivalence factor between, say, g CO_2 equivalents and mL of water contaminated by titanium dioxide entering the waterway.

To conclude the section, Table 11 on page 139 in Appendix D provides a detailed view of the contributions to knowledge and practice made by each appended paper.

Overall, the two methods and the tool developed for RQ1 moderately fulfil the aim of this research.

5.4.3. Answering RQ2

"How can manufacturing companies align their operations with their corporate sustainability strategy?", RQ2 asked.

This research concluded that, in order for manufacturing companies to align operations to sustainability strategy, companies must visualise and control the interaction between strategy, organisational capabilities (especially manufacturing capabilities), sustainability performance indicators of manufacturing and business operations. This research answers RQ2 by giving management a set of guidelines and a tool to maintain and revise the connection between systems that manages and control production systems' sustainability performance. Furthermore, this research proposes a measurement which defines the integrity of such a connection (in other word, alignment).

It was observed that the set of capabilities for sustainable manufacturing which companies owned or wanted to build can be grouped into four archetypes in a 2x2 matrix. It may be said that these archetypes mirror the very concept of corporate sustainability instilled by top management into the manufacturing company; in some cases focused just on the factory rather than the whole product life cycle and focused on two or even just one pillar of sustainability, rather than the whole triple bottom-line.

A rather obvious yet effective answer to RQ2 would seem to lie in human-factor research, social sciences in management research and the decision sciences in corporate environments (such as corporate governance and sustainability leadership). However, this researcher decided to exclude an investigation of those aspects (see Research Scope in Section 1.6) and instead tackled RQ2 from the perspective of a solution encompassed, again, by the realm of sustainability assessments. Choosing this focus does not qualify any sustainability assessment tool/method which measures alignment (or lack thereof) to be a replacement for those excluded disciplines. Rather, the results from sustainability tools/methods which would answer RQ2 may be regarded as a starting point for introducing more complex and nuanced solutions (such as roadmaps and toolboxes in which management theories are applied), which are generated in those domains excluded from human factors/decision-making sciences. Alternatively, the efficacy of the solutions from those domains may be evaluated periodically, say, once a year, with the assessment solutions developed by this researcher.

5.4.4. Contribution and limitations of solutions to RQ2

RQ2 was addressed through the development of a method and a tool.

- The guideline-like method helps top management align sustainability strategy with operations management and describes a taxonomy of strategy implementation for sustainable manufacturing (*Paper V*).

- The tool is a self-assessment questionnaire for measuring the readiness of management to build a desired organisational capability for sustainable manufacturing into their company's operations (*Paper VII*).

Contribution to research and gaps uncovered:

The Capability Methodology for Sustainable Manufacturing (CMSM) partially bridges **gap 3**. The organisational sustainability readiness tool partially bridges **gap 3**. Because the external validation could not have been successfully delivered, **gap 12** remains unbridged.
However, the approach adopted for the development of the organisational sustainability readiness tool was different from other maturity models developed by other academics. The organisational sustainability readiness model was developed from empirical data from six company cases and theories from the literature data. An approach mainly guided by literature review was adopted by all the 25 capability maturity models applied to manufacturing management reviewed in *Paper VII.*
There is a specific reason why the term "readiness" was used, rather than the better-known "maturity". As a semantic choice, this seems legitimate for various reasons. Firstly, the readiness tool encompasses marginal/incremental improvements based only on the company's resources, as opposed to a broader consideration of outward-looking elements (such as engagement with key external stakeholders). Secondly, the use of "readiness" instead of "maturity" was chosen (on a philosophical and behavioural level) to convey that reaching the highest level of the scale signifies a "prepared beginning" for a less unsustainable company, as opposed to a truly sustainable manufacturing company. Furthermore, the state of "prepared beginning" intentionally clashes with the state of "highest maturity", where the latter could make a company lapse into an inertial state from some sort of hard-won wisdom. Thus, this critique applies to other maturity models designed to induce higher sustainability performance in manufacturing organisations. In this sense, this researcher wants the readiness tool to be used by as many companies as may need it, but ultimately becomes that it soon becomes obsolete.

Contribution to practice and practical limitations:

The Capability Methodology for Sustainable Manufacturing (CMSM) prompts top management to think of the concept of sustainable manufacturing and articulate it thought strategy, capabilities and KPIs.

Only two out of the six companies involved in the RQ2 studies had a sustainability formally articulated strategy which had been shared with the company. The other four companies resorted to do-more-with-less thinking [eco-efficiency], which they applied to their traditional business strategy, not dissimilar to the adoption of a lean production philosophy. Consequently, the same conservative thinking was infused in both desired and existing capabilities for sustainable manufacturing (such as “increasing operational efficiency and quality of processes”, as Company I put it).

As an example, a company might want to produce the most durable mechanical equipment for industrial logistics in ports, but fails to see the opportunities for upgrading hardware and software in trucks, meaning that less fuel is consumed during this rather long use phase. This is why the method hints at the consideration of the product life cycle for strategy development purposes and does so via the Complexity – Scope of the product life-cycle matrix. The method also invites us to question the choices of KPIs being tracked in order to achieve the sustainability goals. One example from a company case was that a manufacturing company was striving to be the most sustainable player in its industry (statement not shown verbatim here due to confidentiality issues) but failed to keep track of the location and weight of valuable components and by-products at the shipyard. In some instances, this lack of situational awareness caused “dual production” of certain components.

As previously mentioned, the results of the questionnaire, even though reliant on the well-trusted genuineness of the responses, hint at improvement actions in different company departments. The online questionnaire guarantees scalability and ease of use, which would help to address **gap 1**. However, for the results to be representative of the status of the whole company, a diversity of company roles should be engaged in using the tool and method. This last point also triggers a need for method developers in academia to think further about the different stakeholders in manufacturing companies that will use their methods. Relevant questions are: “which stakeholder would be knowledgeable about certain critical data for the assessment? What are the critical information flows? Who influences these flows?” Some parts of the questionnaire might be profiled for certain company roles, to the exclusion of others, so as to guarantee accurate responses.

There is a final issue concerning the use of maturity-like models. As every model, it simplifies reality and, for some “types of reality”, the model could sometimes offer an unhelpful oversimplification. Improvements made in the real world might not proceed in linear fashion, as displayed by the model, especially for agile production environments dealing with concurring product development and innovation.
Overall, the method and tool developed for RQ2 appeared to fulfil the aim of this research to a limited extent.

Table 11, on page 139 in Appendix D provides a detailed view of the contributions to knowledge brought by the results illustrated in each paper.

5.5. A critical view of the assessment framework

A critical analysis of the assessment framework produced a series of discussion points. These are numbered in the list below. The assessment framework feels the effect of:

1. The blessing and curse of bringing in increased variants for measuring operational and environmental performance of a production system, as opposed to promoting the use of a fewer number of standardised assessment methods and tools.
2. A conundrum in the tool-development approach relating to sizing and scope: one general-purpose tool or many ad-hoc ones?
3. The blessing and curse of having adopted a descriptive approach, based on a pragmatist and constructionist worldview in developing the framework, as opposed to a prescriptive or transformative approach.
4. The trap of short-sightedness from incrementalism and eco-efficiency-thinking in the quest for a solution to the unsustainability challenge.
5. A "flat" currency, chosen to value impact indicators, as opposed to a dynamic one which would reflect the Earth's limited carrying capacity, plus gains and losses in natural capital.

The rest of the section is dedicated to the unravelling of each of the discussion points.

1. *The blessing and curse of bringing in increased variants for measuring operational and environmental performance of a production system, as opposed to promoting the use of fewer standardised assessment methods and tools.*

The first point in the list hints at the existing proliferation of sustainability indicators in the areas of sustainable manufacturing/sustainable production and the plethora of methodologies for sustainability assessment in the literature. As mentioned before, using the proposed assessment framework as a tiny extension to such a vast body of knowledge would be justified, provided it brings a unique contribution once applied in industrial practice. However, this research cannot claim the existence of a contribution purely from developing the framework (and testing of some of its tools) in industrial practice. The reasons behind the lack of a validation effort on the assessment framework.
However, validation efforts were conducted at a tool/method level and revealed concrete opportunities to use of the tools and methods in the assessment framework.

2. *Conundrum in the tool-development approach relating to sizing and scope: one general-purpose tool or many ad-hoc ones?*

The second point in this list presents some connections with the first point. The reason the assessment framework presents several tools and methods for different purposes stems from the inductive reasoning used in developing the framework itself.
Arguably, method developers in academia have two design choices to trade off: complexity vs measurability. If an analysis considers inputs and transformation processes of ecosystems which transcend the company's mere operations, then an increased understanding of the problem's complexity will come at the expense of increased variability and uncertainty in the output measurements. A narrower scope would likely offer more opportunities to measure the desired outputs quantitatively. However, it is difficult to argue whether variability and uncertainty would decrease instead and what the "quality of the quantitative indicators" might be.

3. *The blessing and curse of having adopted a descriptive approach, based on a pragmatist and constructionist worldview in the development of the framework, as opposed to a prescriptive or transformative approach*

In the case of tools and methods for RQ1, the framework measures performance indicators and impact indicators actually originated from pre-set analytical goals from the research projects and/or ordinary needs from top and middle management. In that sense, the framework is "acting pragmatically". Such pragmatism may come at the expense of a lack of perspective (or even *imagination*) in devising or investigating alternative performance indicators better suited to tackling long-term unsustainability challenges.

Considering the organisational level instead (RQ2), the framework comprises methods and tools based on input data from the company sustainability strategy and organisational capabilities for sustainable manufacturing, as declared by management. If the company's top management is the legitimate "process owner" with respect to strategy formulation, then there is no guarantee that the figurative line (where sustainability strategy and operations stand at the end of the advocated alignment process) is the right one for both company and society. This concern is legitimate, especially considering the difficult, long-term challenges; these bring uncertainties which may not be seen or grasped by everyone in top management. This discussion point is therefore about how a "prescriptive transition" should look and what convincing rationale they provide for industry.

4. *The trap of short-sightedness from incrementalism and eco-efficiency-thinking in the quest for a solution to the unsustainability challenge.*

Eco-efficiency as paradigm is well-known as an opportunity to save valuable material and natural resources. As the co-development of tools with industry goes ahead (driven purely by pragmatism and a corporate understanding of sustainability), the risk of veering towards isolated eco-efficiency or even weak sustainability-thinking seems a realistic scenario. Some sustainability scholars have discussed the dangers of an isolated mindset devoted to compliance (with, say, environmental management systems) and the allure of never-ending continuous improvement (kaizen). In discussing sustainable business, Kopnina and Blewitt (2014) highlighted how some critics have noted that, despite the good intentions of eco-efficiency, such a paradigm "only works to slow the process of destruction and perpetuate the bad system, allowing products such as fossil fuels or non-biodegradable plastic to last longer than they otherwise would. Making a system that pollutes and generates waste more efficiently will only prolong an essentially unsustainable system". Furthermore, Kopnina and Blewitt (2014) pointed out how eco-efficiency would ultimately trigger rebound effects (also known as the Jevon paradox), because capitalism requires constant growth.

Assessing a company's improvements in the management of internal resources relating to sustainable manufacturing cannot be done in isolation. It must be coupled with a genuine outward-looking, systemic and consequential approach which considers the projected customers' demands and expectations, market trends and the Earth's planetary boundaries. Adopting a target-based, quota-based approach (similar to the science-based targets with respect to CO_2 emissions) may be a way to successfully implement eco-effectiveness at a corporate level.

5. *A "flat" currency chosen to value impact indicators, as opposed to a dynamic one which would reflect the Earth's limited carrying capacity, plus gains and losses in natural capital.*

In simplified terms, "natural capital" is a form of capital stock identifiable in "trees, minerals, ecosystems, the atmosphere and so on" as opposed to manufactured capital, such as machines and buildings. Both contribute to human welfare (Costanza et al., 1997). A substantial group of scholars (Costanza and Daly, 1992, Costanza et al., 1997, Azqueta and Sotelsek, 2007, Brown and Ulgiati, 2018) (among others) champion (or at least operate mathematically) the conversion of natural capital into financial capital. This aims to integrate environmental and social considerations into corporate investment decisions.

Such integration happens when monetary value is placed on what are deemed "externalities". Of the need for corporations to include sustainability assessment in their financial toolboxes, Maxwell (2015) said: "the social costs or benefits of nature's services are externalities not adequately captured in the market. Companies are not obligated to pay these at present and hence they are not typically considered. However, material externalities may ultimately decrease or increase the value of an organisation, so assessing their effects in business decision-making is critical. By incorporating natural capital into decision-making, the externalities associated with those decisions can be included, bringing these social costs into the cost-benefit framework”.

Tools and methods answering RQ1 were composed by using indicators calculated relative to the number of production parts (such as the e-KPIs,) or “traditional” life cycle impact assessment indicators (like the GWP indicator used to calculate the e-BEP). With respect to the previous two points, such a measurement approach would seem familiar and understandable to a company’s management, but unless physical quotas were set, they would not really *indicate* “containment” actions to ensure that planetary boundaries and environmentally-induced social costs were considered. Furthermore, it is not improbable that the consequences of marginal and incremental variations in LCIA indicators would be “smoothly” understood by key decision-makers in the manufacturing industry, even those genuinely wanting to secure the welfare of a healthy ecosystem. For instance, a CEO concerned about the environmental impact of his/her business might find it hard to appraise the difference between 60 kg CO_2 equivalents per product and 55 kg CO_2 equivalents per product, given the projected customer demand and global need (as yet unallocated per industry) to curb GHG emissions. Is a 5 kg CO_2 equivalent reduction an acceptable decrease or must more be done overall? Such a question could become plausible if directives and prescriptive actions were to be established between a global environmental governance institution and businesses.

Thus, in the future, this researcher advocates “upgrading” and testing the assessment framework, using mechanisms which value natural capital. Furthermore, she would issue an invitation to upgrade existing tools which calculate cumulative societal costs and benefits of a business, in which a resource-based view of the firm is complemented by a stakeholder view of it, grounded in the concept of strong sustainability. However, realising such an upgrade would bring modelling problems tied to moral considerations, such as the discussion on discount rates (whether positive, negative, or nil) applied to social costs payable due to global environmental hazards. An example of this is the historical discussion among scholars on the discount rates for the social cost of carbon (Azar et al., 1996, Pearce, 2003, Tol, 2005, Tol, 2008), especially nowadays in the aftermath of the Nobel-prize winning Dynamic Integrated Climate-Economy model (DICE) Model (Nordhaus, 1992, Nordhaus, 2014, Nordhaus, 2018).

In concluding this discussion, let us recall the aim of this research:

> ***Aim***
> Develop an assessment framework for sustainable manufacturing to make corporate management understand how to positively influence relevant economic and environmental sustainability performance.

In other words, the question which the research now needs to answer is: "does the assessment framework deliver what was intended?"

Given what has just been discussed under points 1 to 5, this researcher concluded that the assessment framework has a moderate chance of being effective, in the following cases only:

- manufacturing companies which do not know "where to start" concerning such themes as sustainability awareness, sustainability strategy and technology assessment for sustainability;
- manufacturing companies where there is lack of communication between top and middle management; the latter occupying a role in product and production development. Arguably, the effects of this broken communication would be especially evident in the area of technology investment decisions and use of performance management systems;
- manufacturing companies with advanced ICT systems at shop-floor level which allow granular monitoring of the energy efficiency performance of machining operations.

For companies fulfilling the above requirements, the use of the assessment framework would still be just a "quick fix" and not a long-term solution, given the needs highlighted in the aforementioned points.

Further points which corroborate the evaluation of the outcome achievable by the framework are:

1. "Green technologies" and well-designed sustainability performance measurement systems may trigger positive change in terms of corporate sustainability performance, in a short or medium-term horizon, but will not be sufficient to sustain the necessary transition of industry towards achieving the 12th SDG.
2. The simple act of informing decision stakeholders about sustainability impacts and performance values may not lead to an effective improvement in a company's sustainability performance. This is a genuine concern about the plausibility of the main assumption underpinning this research and posed on page 3. This concern becomes even more critical with the awareness that sustainability implies a long-term

> commitment to action, discussion and reflection from multiple groups of industrial, political and societal stakeholders. However, having more informed decisions to hand qualifies as first step in achieving more sustainable production systems and manufacturing companies.

Scientists, global-thinking institutions and non-governmental organisations must keep on working with the manufacturing industry. By bringing systems-thinking into solving the unsustainability problem, scientists can pinpoint the risks of dangerous sub-optimisations, help companies see costs and benefits that are not properly accounted for and ensure the achievement of long-term sustainability goals.

6. Conclusion

This research has aimed to play a role in supporting the manufacturing industry in the endeavour to achieve the goal of “sustainable consumption and production”, the 12th goal in the 2030 Agenda set by the United Nations.

An assessment framework for corporate sustainable manufacturing was the result of five years of applied research in 14 company cases.

The assessment framework contains assessment tools and methods encompassing several levels: from low-level analysis (machine tools in a production system) to high-level analysis (the organisation). In this way, the assessment framework aims to induce management to adopt a mindset in which strategy and operations should synchronise to achieve the desired sustainability goals.

At the lower level of analysis, two novel key performance indicators were developed: 1) an energy-based overall equipment effectiveness indicator and 2) an indicator for environmental break-even analysis of R&D technologies. The former diagnoses causes of energy inefficiencies in production. The latter allows undesired environmental backfire effects from new technology to be avoided.

At the higher level of analysis, a questionnaire tool diagnoses the readiness level of a manufacturing company’s operation in acquiring the desired capabilities for economic and environmentally sustainable manufacturing (such as zero waste, pollution prevention), given how technical and information systems in the company are managed.

Validation studies showed that using the results from the novel tools and methods in the assessment framework, the management of manufacturing companies is equipped with new quantitative and qualitative information, allowing them to become consistently and systematically more economical and environmentally sustainable. The assessment framework contributed to shortening some of the gaps between the mature field of sustainability assessments developed by researchers and the applicability of these assessments in the industrial practices of the manufacturing industry. The framework addresses key efficiency matters in manufacturing companies and opens the way to focus on the most challenging eco-effectiveness issues. Addressing these issues can contribute to a safer future that remains environmentally accountable at all levels of business operations.

Chapter 6: Conclusion

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Appendixes

Appendix A – concept map of surveyed literature

Figure 23 is a conceptual map in which each concept (in an oval) represents a keyword of this research. In *Figure 23*, the themes presented in the previous section appear as connecting concepts between two or more ovals. Furthermore, each oval was given a similar name to the title of the digital folder (repository) used by this researcher to store publications. The reader is invited to observe the notation and colour code and thus comprehend the extent to which each concept or theme was relevant to this research. The method this researcher used to compile the literature data and produced this map is explained on pages 54-55.

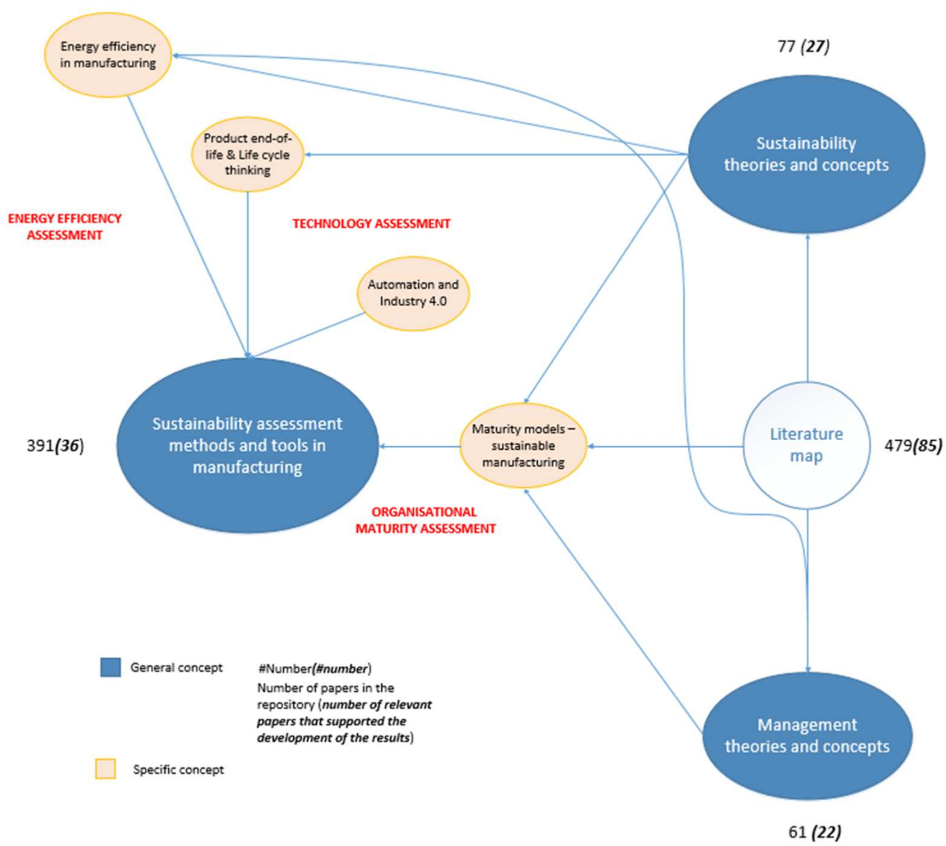

Figure 23: Concept map of surveyed literature

Appendix B– interview protocol

Interview questions for eliciting company strategy and core capabilities for sustainability in manufacturing companies - used in Paper V

Disclaimer: these interview questions were used in a research study aiming to define the organisational maturity and operational core capability of manufacturing companies from a sustainability perspective. The ultimate aim of the research study is to come up with a methodology which helps top management in manufacturing companies to frame a strategy for sustainable manufacturing and align their capabilities to it. Part of the study was conducted in collaboration with UNSW Sydney. Ilaria Barletta, PhD student at Chalmers University of Technology, developed the interview questions.

"Company X" represents a generic manufacturing company, as the object of the study.

Thirteen questions have been grouped into six thematic areas: 1) company's purpose and value proposition, 2) definition of sustainable manufacturing and sustainability, 3) core capabilities, 4) challenges for business sustainability, 5) characterisation of the ecosystem critical to the company's environmental and 6) social sustainability.

KNOWING THE INTERVIEWEE'S BACKGROUND

1. What do you do in Company X?
2. How long ago did you start?

COMPANY'S PURPOSE and VALUE PROPOSITION

3. What is the driving purpose of Company X? In other words, what are the reasons that motivate its existence on the market?
4. How does Company X provide value to its customers?
5. What guarantees its competitiveness?

DEFINITION OF SUSTAINABLE MANUFACTURING and SUSTAINABILITY

6. How would you define sustainable manufacturing?
7. Would you recognize the differentiation of it into economic, environmental, and social sustainability? (pillars of sustainability)
8. What is Company X's strategy with respect to sustainability? E.g., targets set by regulatory body and cascading goals, or operational targets and cascading goals.

CORE CAPABILITIES

9. Are you familiar with the concept of organisational core capabilities of a company?

   If the respondent is not, the interviewer introduces the concept to him/her and provides examples.
10. What are the core capabilities that allow Company X to provide such value?

CHALLENGES FOR BUSINESS SUSTAINABILITY

11. What is the main challenge that Company X has to tackle in order to stay competitive in the near future (e.g., 10 years)?
12. And in the middle-long term future? (e.g., 50-100 years)

CHARACTERIZATION OF THE ECOSYSTEM THAT IS CRITICAL FOR COMPANY'S ENVIRONMENTAL AND SOCIAL SUSTAINABILITY

13. While picturing Company X’s products life cycle (from cradle to grave/cradle), can you characterize within it the key stakeholders that play a major role in Company X’s sustainability performances?

Appendix C– capabilities for sustainable manufacturing

Table 9 includes a list of capabilities which Companies H to M considered "core" to realising their corporate sustainability strategy. This list is a key part of the data collection activities from the focus groups and interviews for Studies 4.1 and 4.2 (RQ2).

Table 9: Sustainable manufacturing capabilities in company cases in Study 4.1 and Study 4.2 (RQ2).

Company	**Industry**	**Sustainable manufacturing capability**
H	Machinery: starch moulding equipment	Product modularity
		Refurbishment of old moguls (mogul =product)
		Easy product maintenance by customer
I	Machinery: construction machinery and heavy trucks	Product modularity and customisation
		Continuous improvement of internal efficiency and production quality performance
		Mobile software (e.g., apps) to track customers' effective use and maintenance practices
		Keeping up with new technology at factory level
J	Life science tools and services. Prescription glasses	Producing a durable yet flexible frame
		Closing the material loop as much as possible in the product's bill of materials
		Product modularity
K	Transportation infrastructure. Ship repair	Punctuality of a wide range of ship-repair operations
		High-quality standard of a wide range of ship-repair operations
M	Marine. Cruise ships	Resource efficiency at the shipyard (beyond steel)
		Zero waste production and keeping resources and values in the loop
		Information transparency of the bill of materials (BOM) across the product's life cycle
L	Transportation infrastructure. Ship repair	Resource efficiency at the shipyard
		Product quality (precision of component sizes)
		Efficient and effective retrofitting

Appendix D – supporting tables

Table 10 resumes the quality criteria illustrated in Table 5 and adds tactics which scholars of research methodologies suggested in order to ensure research rigor and trustworthiness. See the references in the "Source" column for information on each tactic.

Table 10: Tactics for trustworthiness of research per quality criterion. Main structure of the table adapted from Guba (1981) and Yin (2009).

	Quality Criteria	Relevant tactics	Source
Quantitative paradigm	Internal validity	• pattern matching • explanation building • rival explanations • logic models	(Yin, 2009)
	External validity	• theory in single case designs • replication logic in multiple-case designs	(Yin, 2009)
	Reliability	• case study protocol • case study database	(Yin, 2009)
	Objectivity	• others (peers, external auditors) examine the data • de facto, the fulfilment of the tactics above	(Creswell and Plano Clark, 2011)
Qualitative paradigm	Credibility	• thick descriptions • member checking • triangulation and crystallisation • partiality	(Tracy, 2010)
		• prolonged engagement • collaboration	(Creswell and Miller, 2000)
		• adoption of appropriate, well recognised research methods • development of early familiarity with culture of participating organisations • random sampling of individuals serving as informants • tactics to help ensure honesty in informants • iterative questioning in data collection dialogues • negative case analysis • peer scrutiny of project • use of "reflective commentary" • description of background, qualifications and experience of the researcher	(Shenton 2004)

Quality Criteria	Relevant tactics	Source
	• examination of previous research findings	
Transferability	• disconfirming evidence	(Creswell and Plano Clark, 2011)
	• thick descriptions	(Shenton 2004) (Tracy, 2010)
Dependability	• intercoder agreement	(Miles et al., 1994)
	• reporting on research design and implementation • reporting on data gathering • employment of “overlapping methods” • reflective appraisal of the project	(Shenton, 2004)
Confirmability	• others (peers, external auditors) examine the data	(Creswell and Plano Clark, 2011)
	• audit trail	(Creswell and Miller, 2000)
	• admission of researcher’s beliefs and assumptions • triangulation	(Shenton, 2004)

Table 11 illustrates the contributions to the RQs per paper and the limitations, mainly from a practical standpoint. The extent of each contribution in answering the RQ is qualitatively expressed in the rightmost column of the table using the color-coded notation:

- ● Relevant contribution
- ◍ Mild contribution
- ○ Minor contribution

Table 11: Contributions and limitations of the core papers.

Paper #	Title	RQ	Contributions in terms of advancement of the research and adoptability in practice.	Quality of contribution
I	Barletta, I., Andersson, J., Johansson, B., May, G. and Taisch, M., 2014, December. Assessing a proposal for an energy-based overall equipment effectiveness indicator through discrete event simulation. In Proceedings of the Winter Simulation Conference 2014 (pp. 1096-1107). IEEE.	1	Contribution within the area of indicator-based decision support tools for energy management in production systems. Advancement of the research area by testing an indicator to diagnose energy inefficiencies of machine tools (Energy OEE) in a simulation environment. The test in DES makes the indicator “relatable” to use in industrial applications where production systems are equipped with advanced sensoring. Limitations: energy efficiency in electricity consumption as the only economic and environmental performance area that was considered. An overly reductionist view of the production system considered as a line of machine tools.	◍
II	May, G., Barletta, I., Stahl, B., and Taisch, M. 2015. Energy Management in Production: A novel Method to Develop Key Performance Indicators for Improving Energy Efficiency. Applied Energy, 149, pp. 46-61.	1	Contribution within the area of indicator-based decision support tools for energy management in production systems. Advancement of the field by developing a method to generate novel energy-related KPIs (e-KPIs) for tracking energy inefficiencies’ leading factors, stemming from management decisions (e.g. quality, use of machine tool). Limitations: same as above.	●
III	Barletta, I., Larborn, J., Mani, M. and Johansson, B., 2016. Towards an Assessment Methodology to Support Decision Making for Sustainable Electronic Waste Management Systems: Automatic Sorting Technology. Sustainability, 8(1), p.84.	1	Contribution within the area of sustainability assessment tools and methodologies for production systems. Limitations: production systems dedicated to products’ end-of-life stage only (e.g. sorting, disassembly). The study is not based on a structured understanding of research gaps obtained from a systematic literature review.	○
IV	Rebouillat, L., Barletta, I., Johansson, B., Mani, M., Bernstein, W.Z., Morris, K.C., and Lyons, K.W. 2016.	1	Contribution: the application of a business process-modelling standard for manufacturing process characterisation has been used as tool to understand the potential of categorising sustainability-related data in	○

Paper #	Title	RQ	Contributions in terms of advancement of the research and adoptability in practice.	Quality of contribution
	Understanding Sustainability Data through Unit Manufacturing Process Representations: A Case Study on Stone Production. Procedia CIRP, 57, pp. 686-691.		production (e.g. fuel use for inbound logistics in quarries) for performance improvement purposes. Limitations: this research effort is intended to be a possible prerequisite for environmental performance improvement, rather than an assessment method/tool as such. No external validation and no “structured” internal validation (e.g. via questionnaire or focus groups).	
V	Barletta, I., Berlin, C., Despeisse, M., Van Voorthuysen, E. and Johansson, B., 2018. A Methodology to Align Core Manufacturing Capabilities with Sustainable Manufacturing Strategies. Procedia CIRP, 69(1), pp.242-247.	2	Contribution: the methodology provides guidelines which support strategic alignment with operations in the field of corporate sustainable manufacturing. The Complexity-Scope of product life-cycle matrix was considered helpful in categorising archetypes of sustainability-strategy development, from the perspective of the companies which contributed to develop the method. Limitations: the method is in turn composed by several methods and tools (e.g., the one in Paper VII) that need to undertake internal and external validity tests so that a conclusion can be made on the contribution of the overarching method.	●
VI	Barletta, I., Despeisse, M. and Johansson, B., 2018. The Proposal of an Environmental Break-Even Point as Assessment Method of Product-Service Systems for Circular Economy. Procedia CIRP, 72(1), pp.720-725.	1	Contribution: an assessment method for environmental costs and benefits of a piece of technology for production systems, given the knowledge of market demand scenarios and production rates. Limitation: low novelty. Method transplanted from the parent method used in managerial economics. Implementation relies on a previous LCA analysis of the technology (in its manufacture and operative stages) and on the product end-of-life scenarios. The method garnered different reactions from potential users.	●
VII	Barletta, I., Despeisse, M., Hoffenson, S., Mani, M., and Johansson, B. (-) An Organisational Sustainability Readiness Tool for Manufacturing Companies. Submitted to Business Strategy and the Environment.	2	Contribution: the readiness tool aims to capture the alignment between operations and sustainability strategy using a resulting score. It enriches the academic literature on capability management and capability maturity in corporate sustainability. Limitations: the number of testers of the readiness tool (six people) is insufficient for any strong conclusion pertaining to internal validity.	○

Appendix E – data collection templates for validation purposes

Questionnaire sent for validation of decision-support methodology for technology assessment in production (Paper III)

A five-question questionnaire sent in October 2015. The text of the questionnaire starts with the following sentence:

Express the extent of the value that the decision support tool would bring to your company.
The evaluation scale is:

1	2	3	4	5
No value	Partially valuable	Fairly valuable	Valuable	Very valuable

You can directly cross or underline the cell you selected and get back to us by replying to this email.

1. How would your company value the benefit from a virtual model of your complete facility showing resources' utilization, capacity, energy consumption, and throughput?

1	2	3	4	5

2. How would your company value the benefit from a model where you can compare economical return of investments of various systems for waste management?

1	2	3	4	5

3. How would your company value the benefit from a model where you can compare and understand environmental incentives for waste management?

1	2	3	4	5

4. How would your company value the benefit from having a better understanding of actors and their relationships in your supply chain of waste management?

1	2	3	4	5

5. Overall, how would your company value the benefit from a tool embedding all the functionalities listed above to support the decision making process?

1	2	3	4	5

Questionnaire sent for validation of the environmental break-even analysis of new technologies in production (Paper VI)

A five-question questionnaire was sent in January 2017. The text of the questionnaire starts with the following sentence:

This five-question survey aims at validating the environmental break-even analysis, as per explained in this 4:30 minute-video (please download it at https://drive.google.com/open?id=1ruAlgoUU4mDg6T3MgoV23IUE1xQldiw7)

1. In which macro-sector do you work?

- Industry
- Academia
- Others

PURPOSE

2. Rate your agreement on the following statement:

   "I understand the reason why management would use the environmental break-even analysis"

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree

USABILITY

3. Rate your agreement on the following statement:

   "I understand the basic methodology underlying the environmental break-even analysis".

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree

USEFULNESS

4. Rate your agreement on the following statement:

   "The environmental break-even analysis is useful for management in guiding decisions on technology adoption from an environmental standpoint".

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree

EFFECTIVENESS

5. Rate your agreement on the following statement:

   "The environmental break-even analysis is helpful for management in understanding the implications of the results from environmental assessments from a product and production-life cycle perspective"

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree

Questionnaire sent for validation of the organisational readiness assessment for sustainable manufacturing (Paper VII)

Once the respondent answers all the questions, he/she visualises the results as follows:

The average sustainability readiness score of your organisation is [result of average] with a standard deviation of [result of standard deviation].
The levels of readiness range from 0 to 3, and refer uniquely to the readiness/fit in building the sustainability capability. The meaning of the scores is the follow:

- 0 - unprepared: your organisation is not ready to build the sustainable manufacturing capability across management systems (manufacturing processes, assets, materials, data-driven decision support, information systems, and organisational competences).
- 1 - novice: your organisation is learning to build the sustainable manufacturing capability across its management systems.

- 2 – almost ready but static: your organisation has just built the sustainable manufacturing capability across its systems, but does not secure continuous improvement of the performance connected to the capability.
- 3 - ready, continuous improver: your organisation built the sustainable manufacturing capability across its systems and strives for continuous improvement of the performance connected to the capability.

Summary of the results per system at the date [current date]:
Notes: Min Mean=0, Max Mean=3. The answer "None of the statements is applicable" does not affect the statistics.

	Mean	Standard deviation
Process management		
Asset management		
Material management	Automatically populated by the piece of software	
Information systems		
Data driven decision support		
Organisational competences		

Note: the respondent downloads a pdf of all his/her questions + answers
Given the results above, the validation occurs as per following questions:

39. Rate your agreement on this statement: “these results suggest the priorities to tackle by management for increased sustainability performance with respect to X”.

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree

Note: Logic built in the software: if the answer to #39 is “Neither agree nor disagree” or “Somewhat disagree” or “Strongly disagree”, then the software points to the following question, #40. Otherwise, the following question is #41.

40. Why is this so? (Multiple selection is allowed)

- The answers to the questions did not describe the situation of my company
- The questions were unclear

- The values of the scores did not address a specific pain point in the organisation
- I need to discuss the results from the survey with other decision makers of my company
- NA

41. Rate your agreement on this statement: “these results suggest a specific course of action for increased sustainability performance with respect to “X”.

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree

Note: Logic built in the software: if the answer to #41 is “Neither agree nor disagree” or “Somewhat disagree” or “Strongly disagree”, then the software points to the following question, #42. Otherwise, the following question is #43.

42. Why is this so? (Multiple selection is allowed)

- The answers to the questions did not describe the situation of my company
- The questions were unclear
- The values of the scores did not address a specific pain point in the organisation
- I need to discuss the results from the survey with other decision makers of my company
- NA

Note: End of the survey, if the respondent ends by answering this question.

43. Which action would you implement first?

Free text.

Note: End of the survey, if the respondent ends by answering this question.

Appendixes